Oscillation Experiments With Accelerators

April 2011 Meeting of the American Physical Society
April 30-May 3,
Anaheim, CA

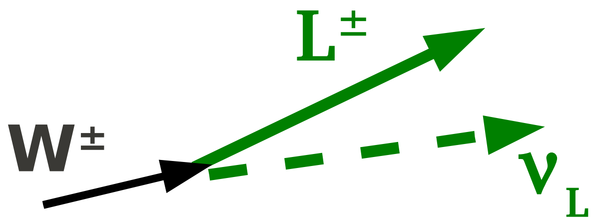
Mike Kordosky

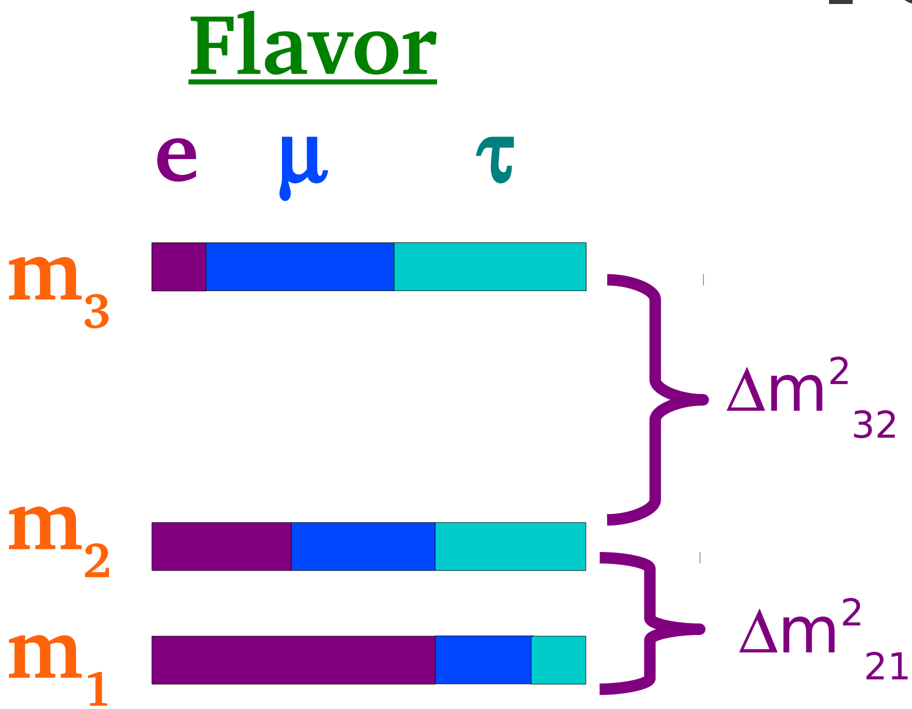
William & Mary
May 1, 2011

Plan For This Talk

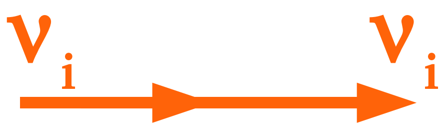
- Neutrino mixing and oscillations
- Experimental methodology
  - Neutrino beams
  - Measurements with a near detector
  - Predicting the far detector
  - Extraction of oscillation parameters
- Experimental results: MINOS, T2K, OPERA
  - Muon neutrino disappearance
  - Electron Neutrino appearance

Oscillation Formalism





Mass



$E^2 = p^2 + m_i^2$

PMNS
Mixing Matrix

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

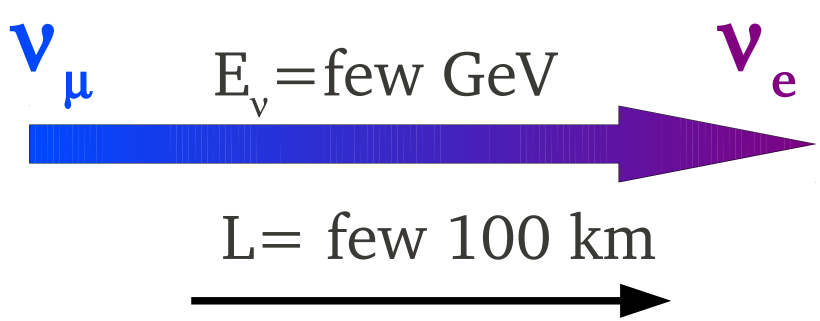
Propagation (vacuum)

flavor mass states

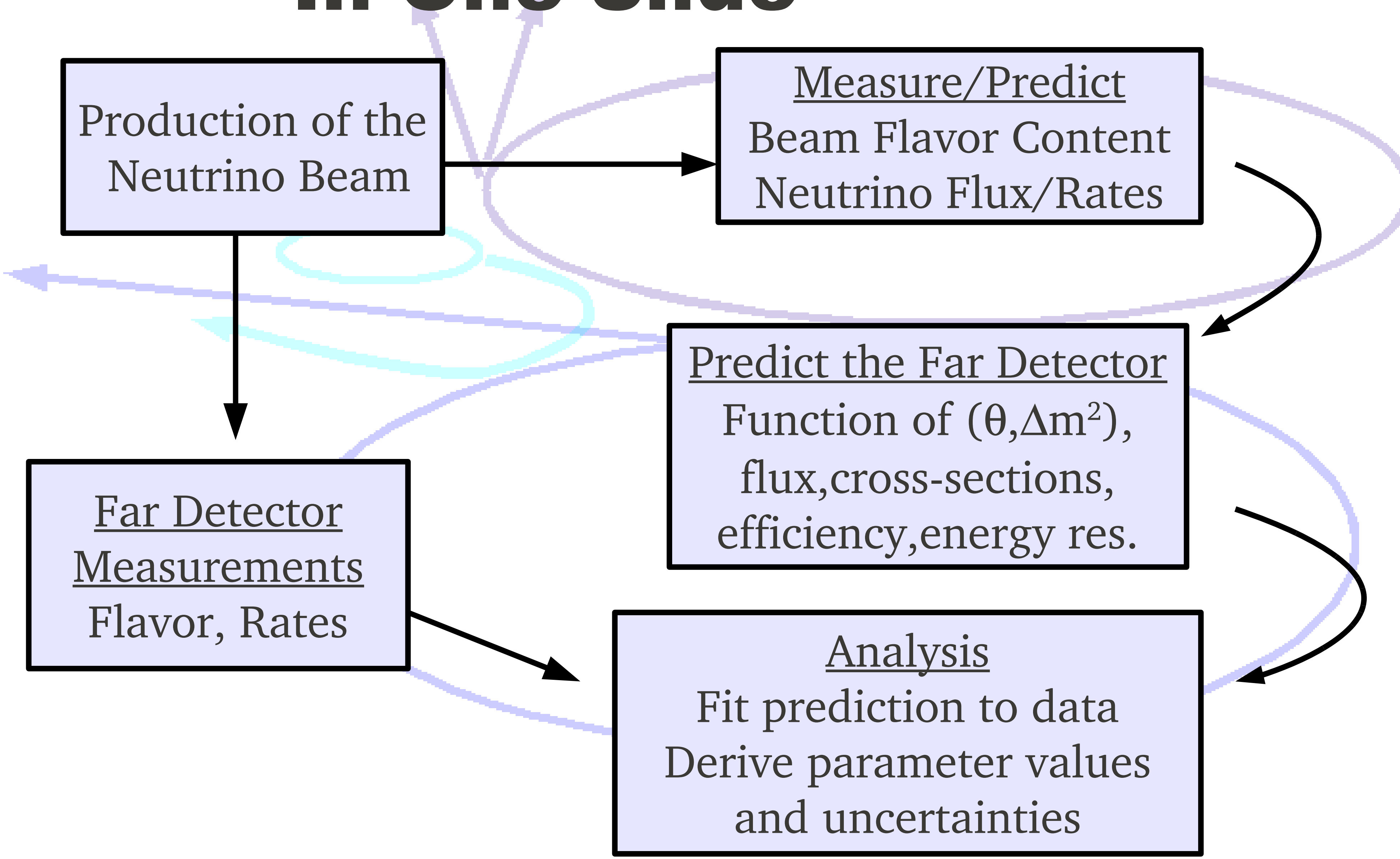
$$|\nu_\alpha(L)\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle \exp(-i L m_j^2 / 2p)$$

(L=distance)

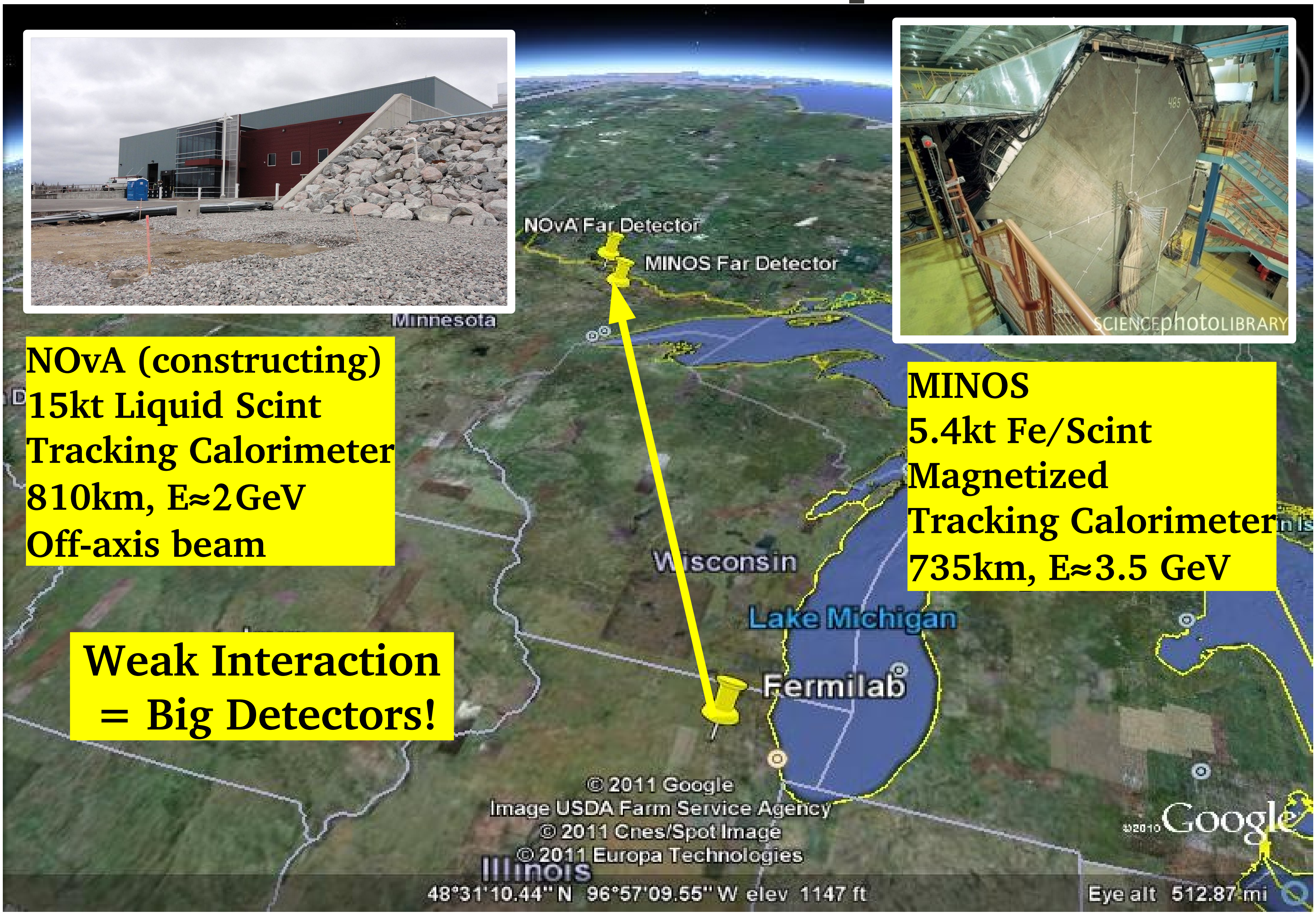
Flavor change



An Accelerator Experiment In One Slide



Where are these experiments?



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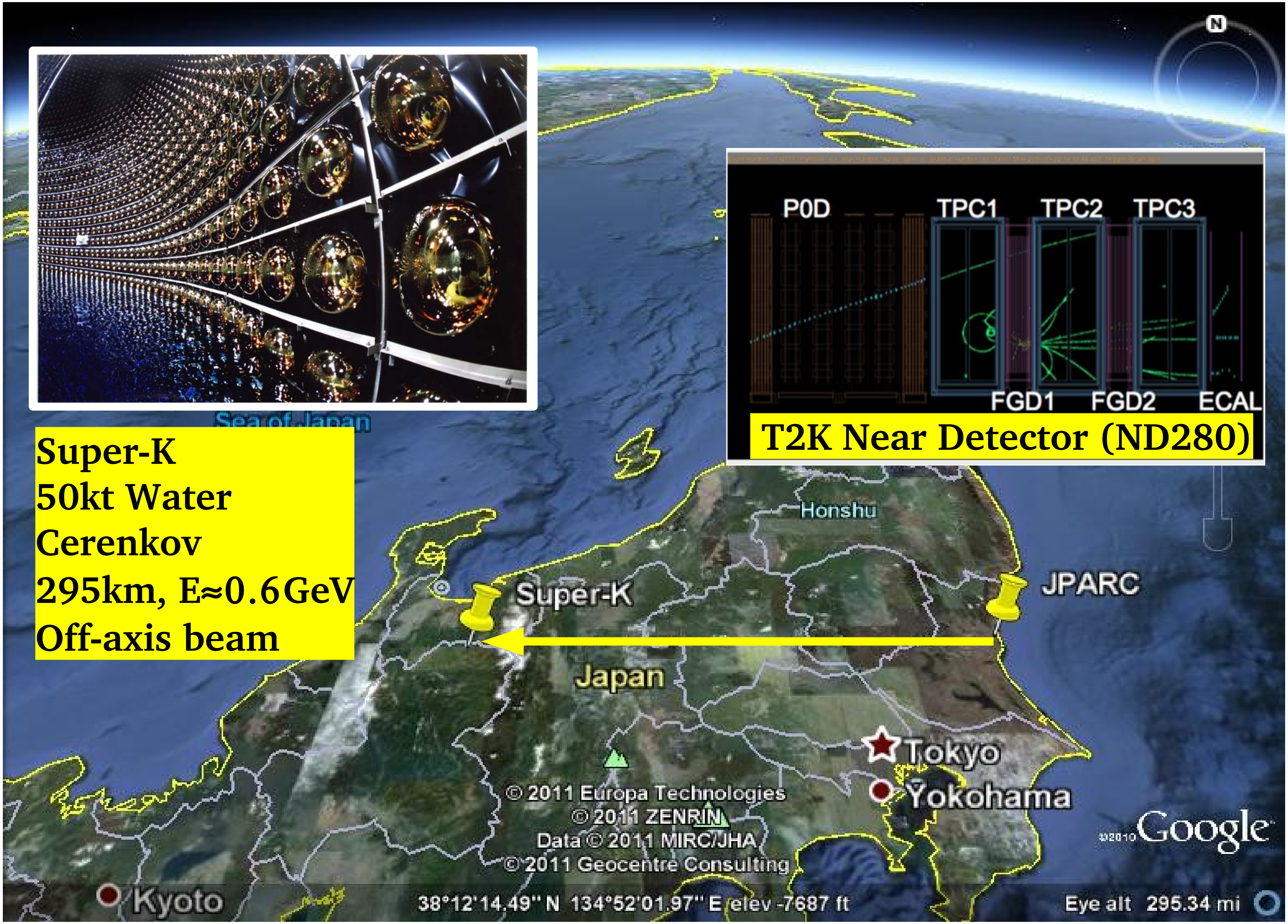
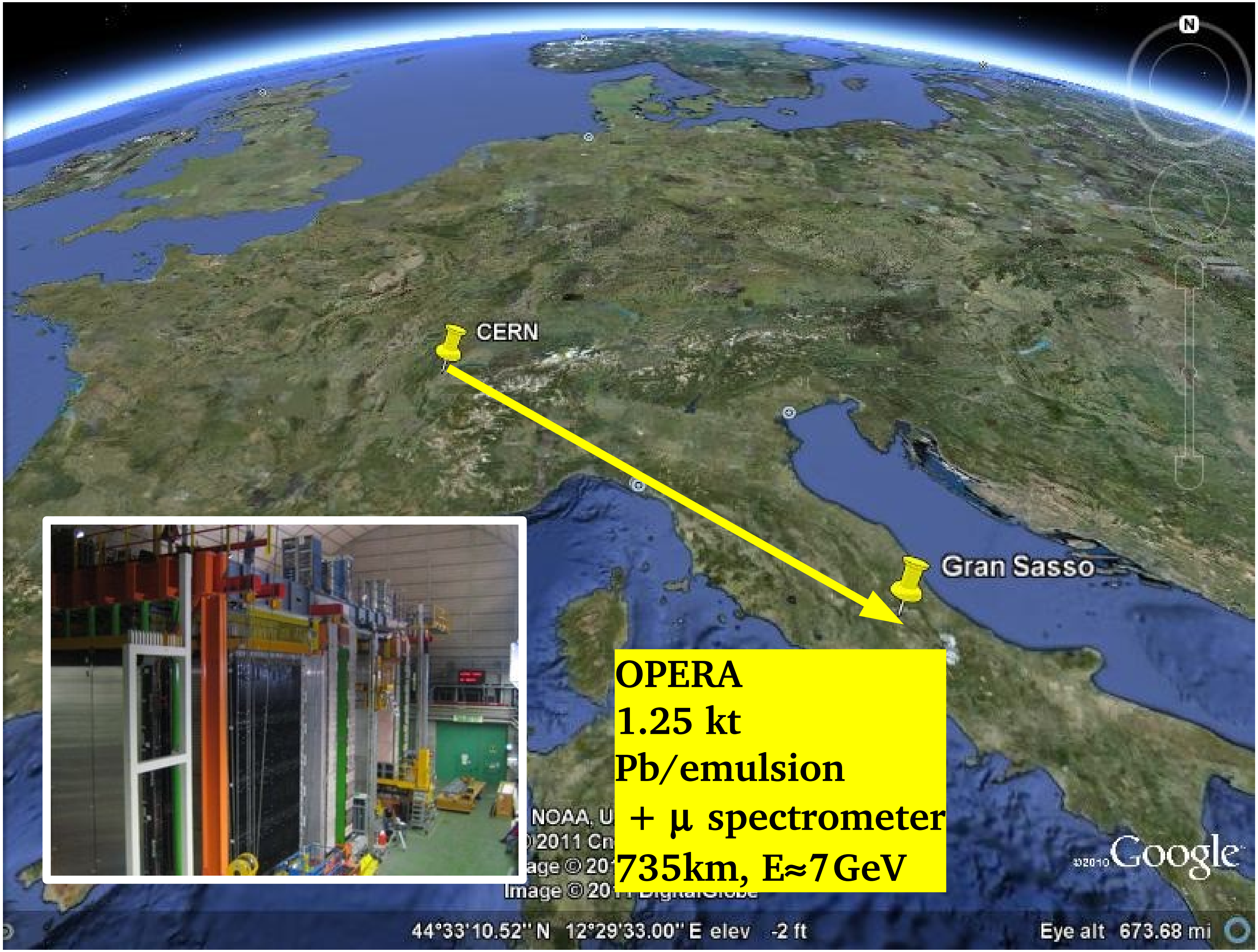
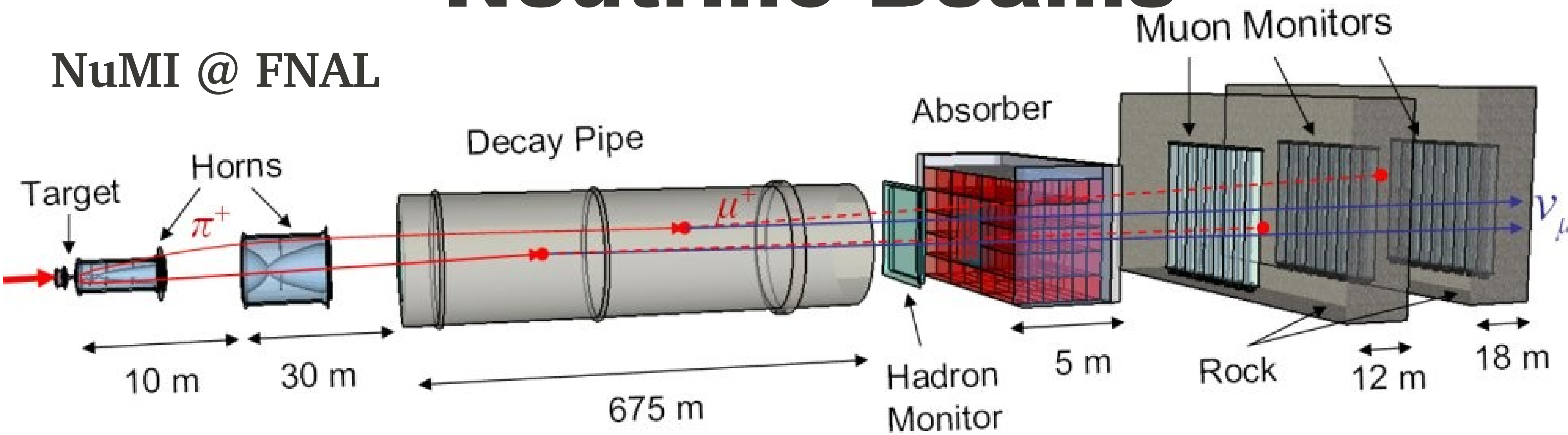


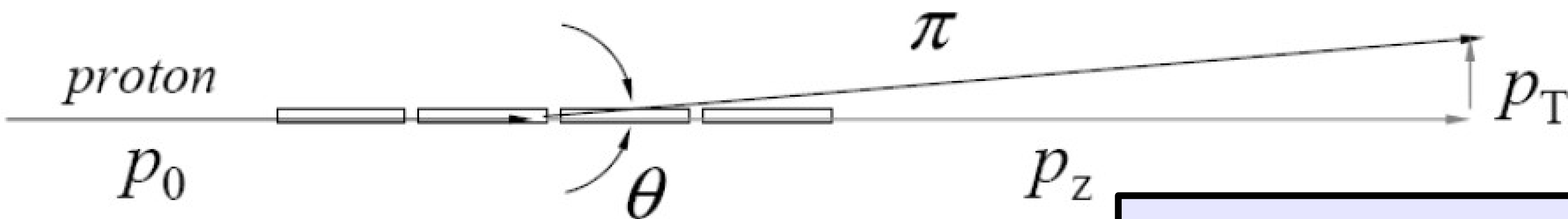
Where are these experiments?



Neutrino Beams

NuMI @ FNAL





- π,K production off a solid target
- Wide range of pt, pz
- Cross-sections not well known

Important decay modes

$\pi^+, K^+ \rightarrow \mu^+ \nu_\mu$

$K^+ \rightarrow \pi^0 \mu^+ \nu_\mu, \pi^0 e^+ \nu_e$

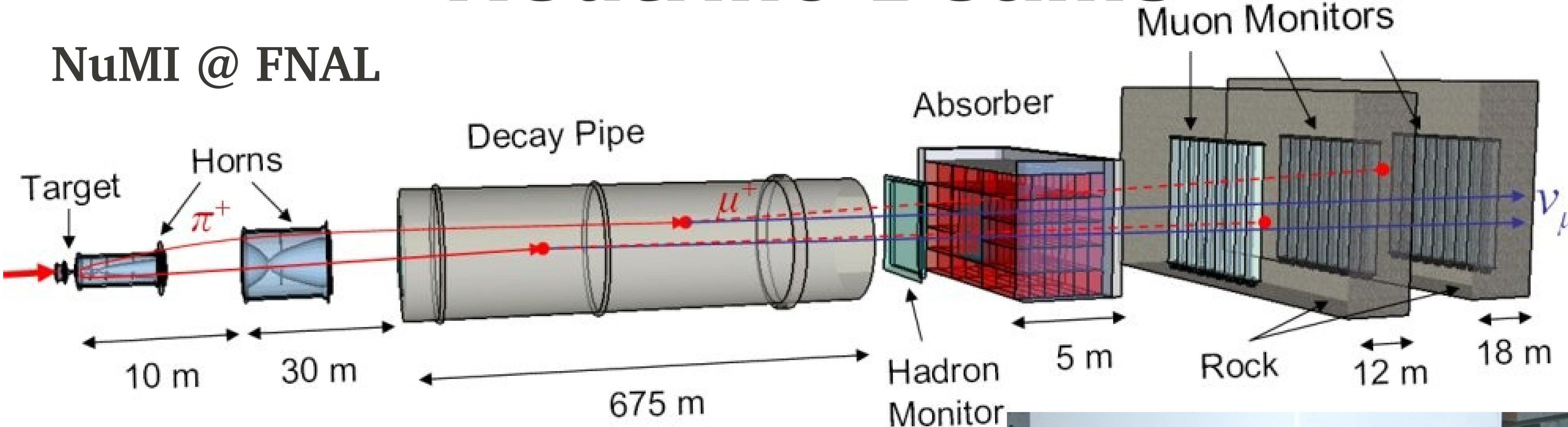
$K^0_L \rightarrow \pi^- e^+ \nu_e$ + CC

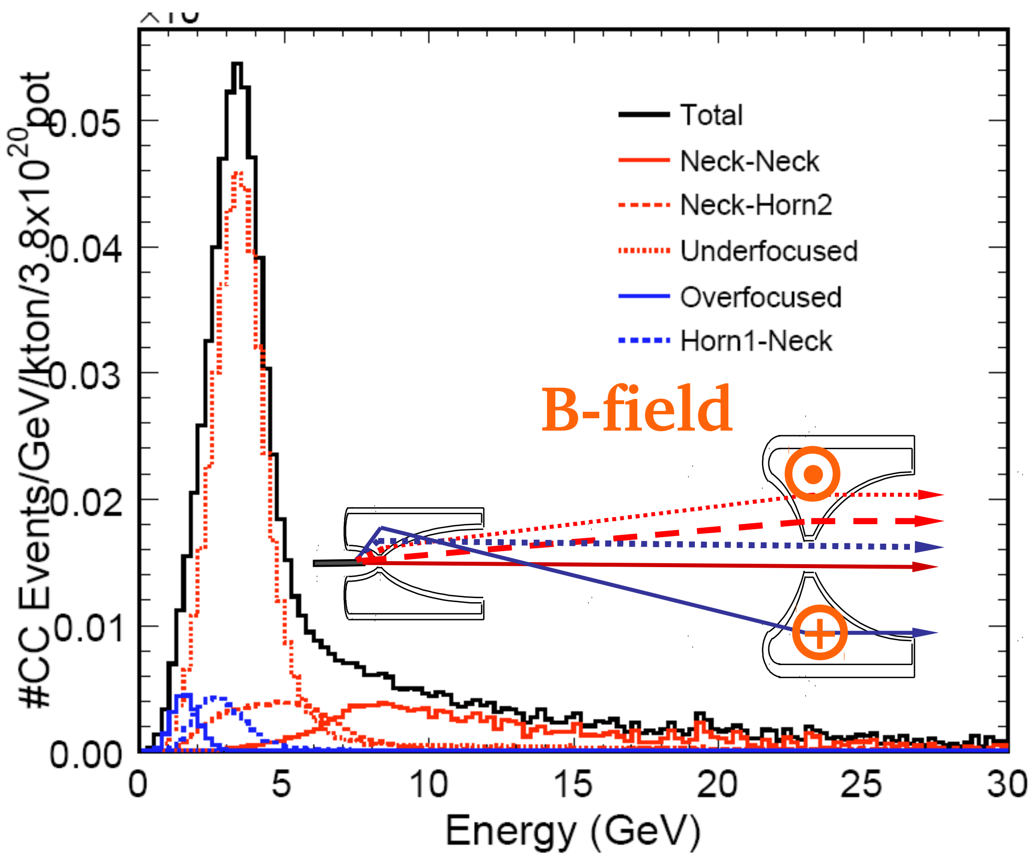
$\rightarrow \pi^- \mu^+ \nu_\mu$ +CC

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

Neutrino Beams

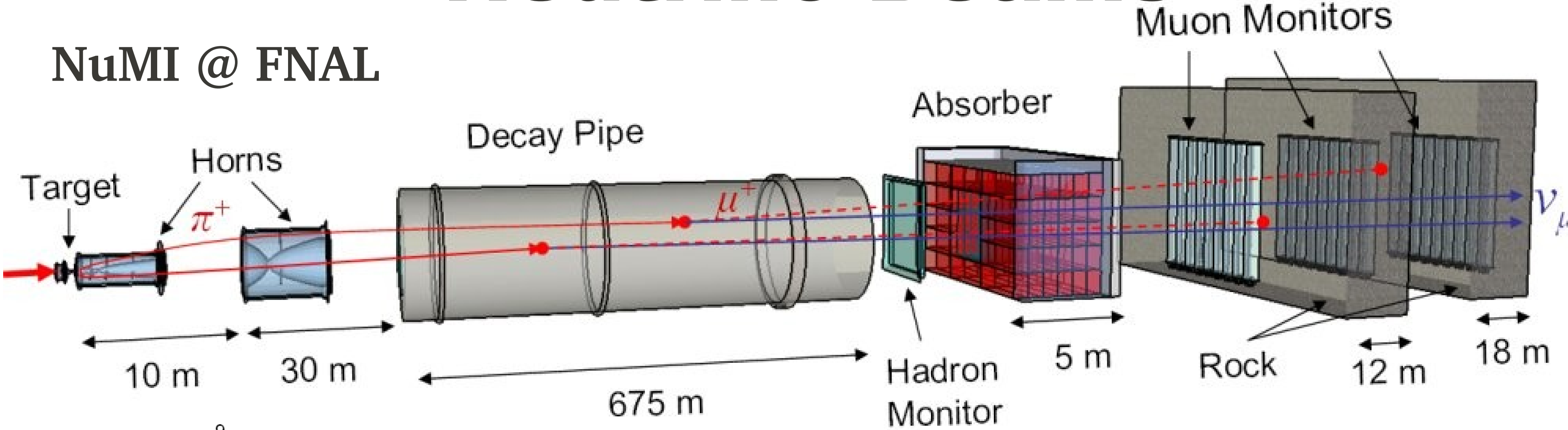
NuMI @ FNAL

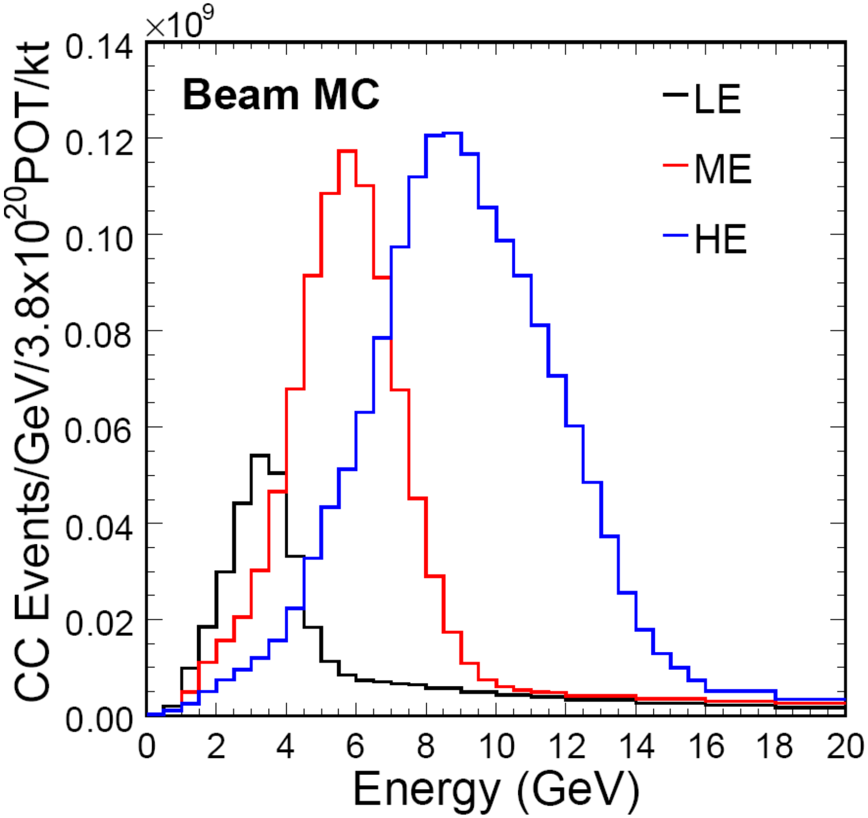


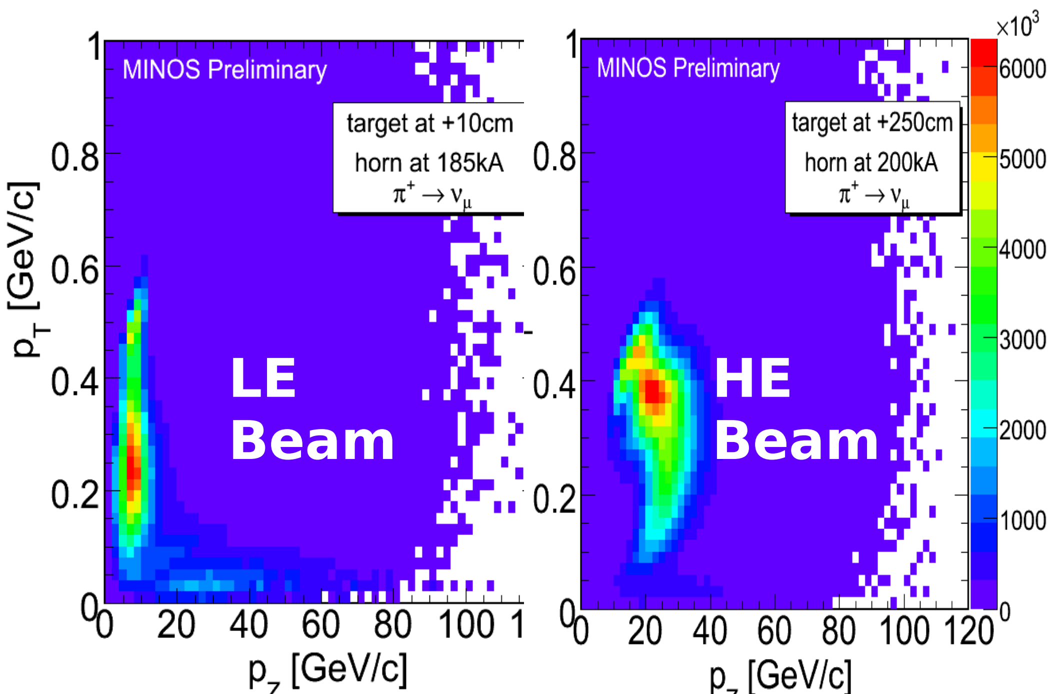


Neutrino Beams

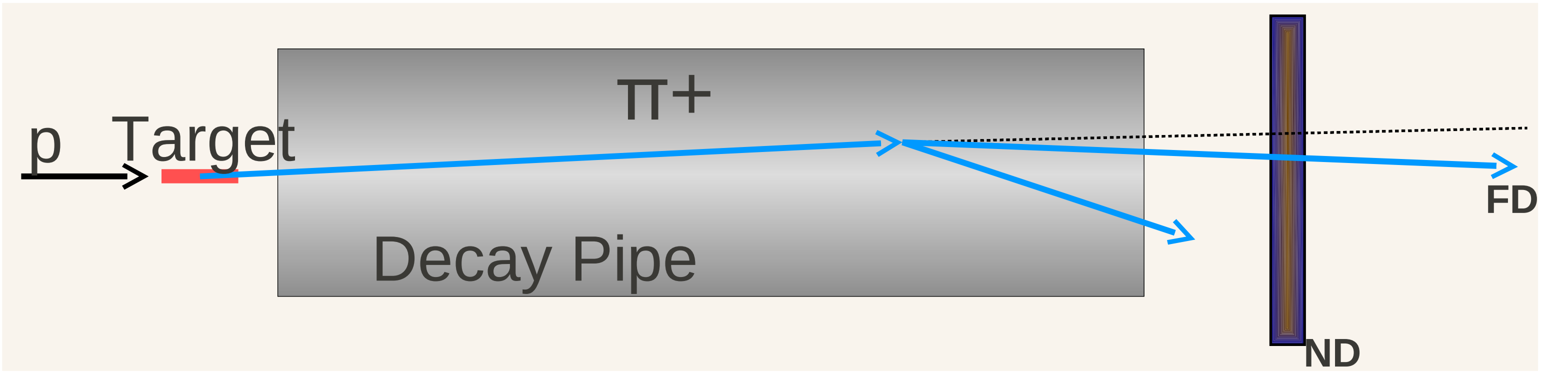
NuMI @ FNAL



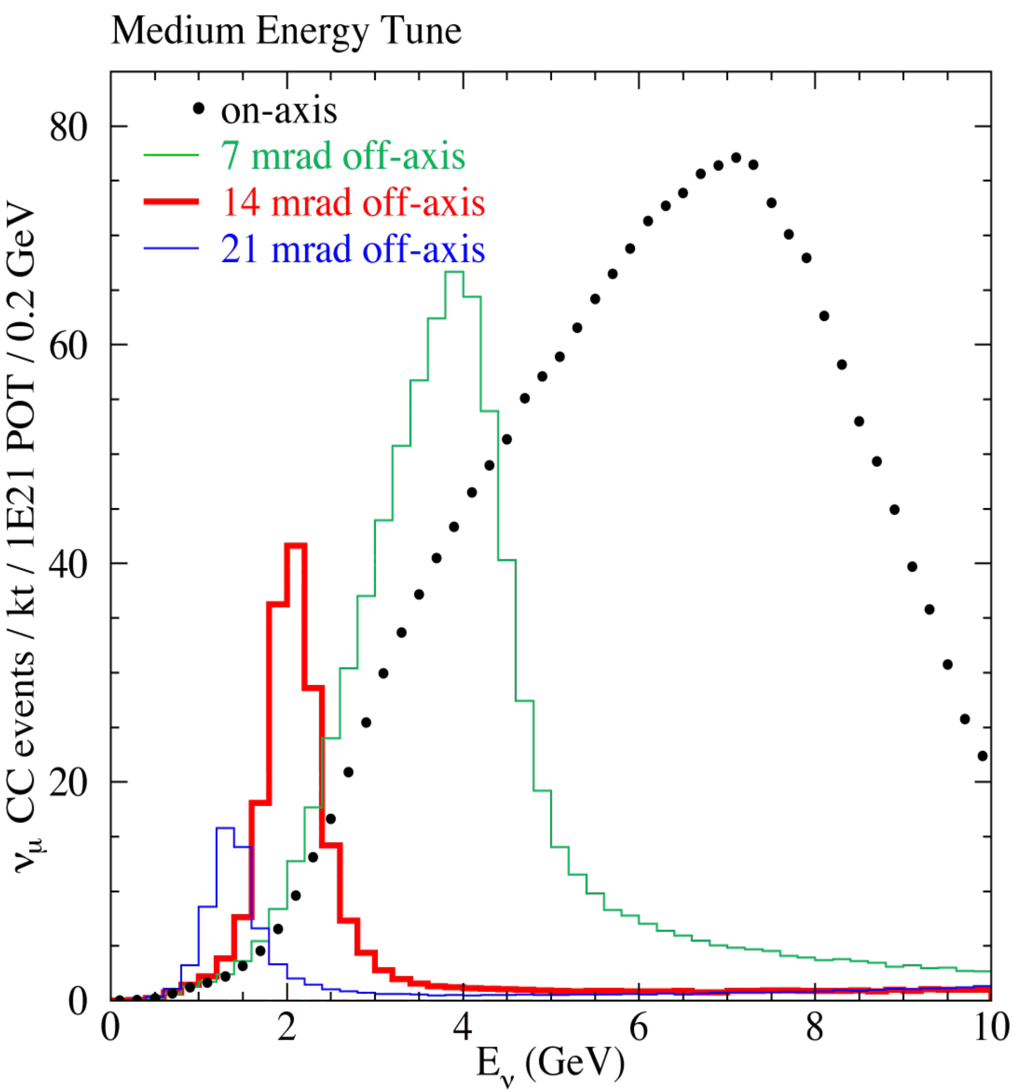




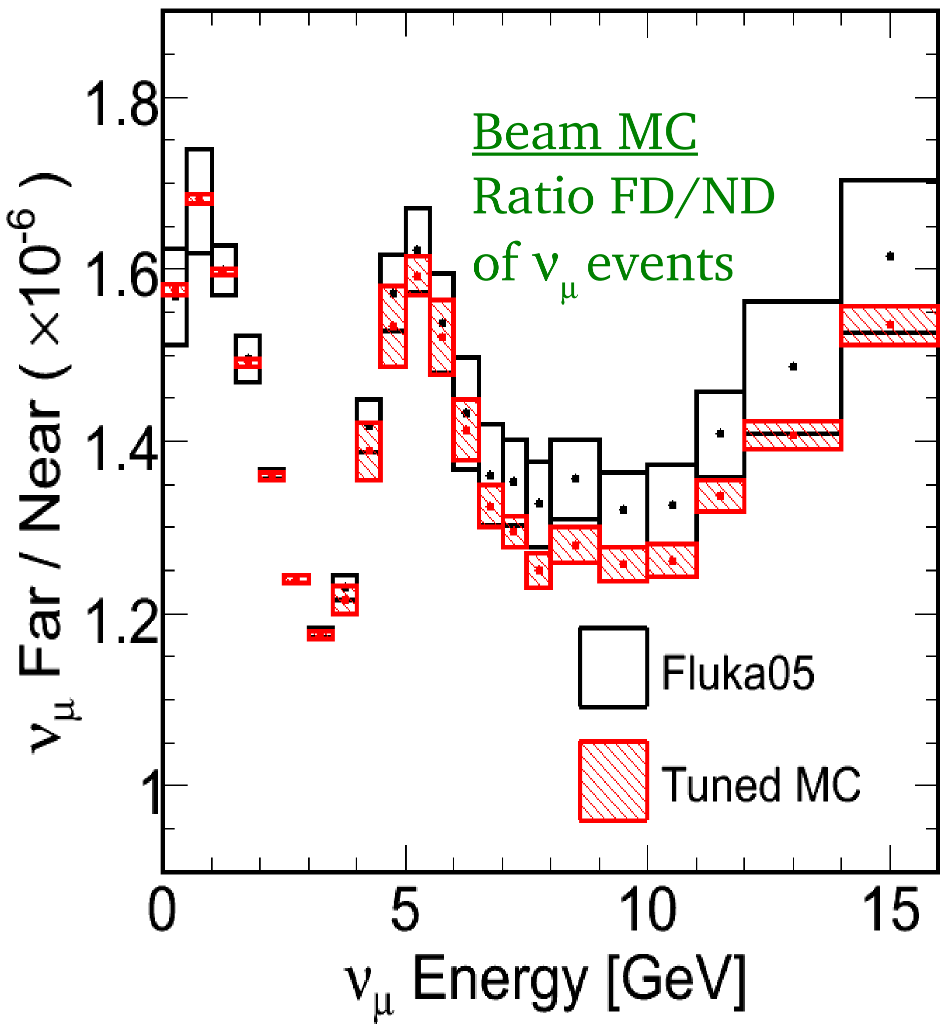
Decay



π+
p
Target
Decay Pipe
FD
ND

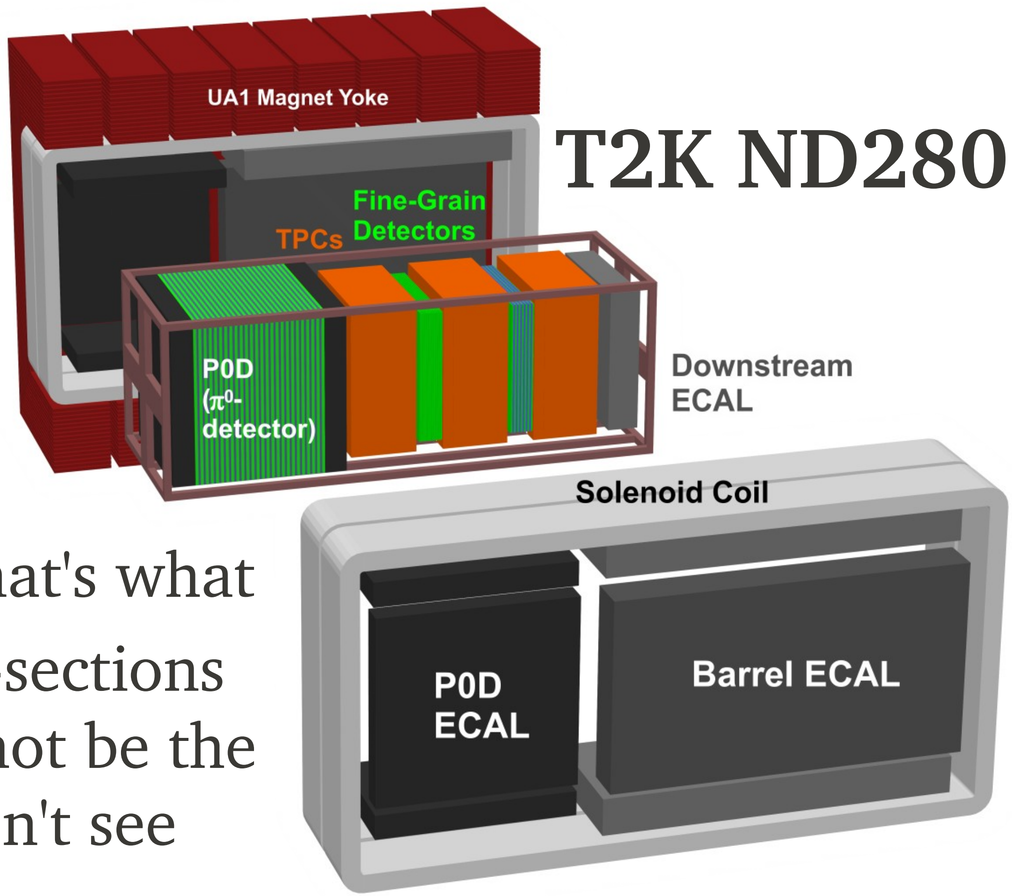


Medium Energy Tune
on-axis
7 mrad off-axis
14 mrad off-axis
21 mrad off-axis
ν_μ CC events / kt / 1E21 POT / 0.2 GeV
E_ν (GeV)



Beam MC
Ratio FD/ND
of ν_μ events
Fluka05
Tuned MC
ν_μ Far / Near ($\times 10^{-6}$)
ν_μ Energy [GeV]

The Ultimate Monitor...



...is a near detector.

Oscillations are sensitive to E_ν and that's what an ND measures. This folds in cross-sections and acceptance, which may or may not be the same as at the FD. Also, the ND doesn't see exactly the same beam as the FD.

Rough Sport

Horns, targets, monitors & windows are consumables of a neutrino experiment

JPARC — OK so far!
1.45e20 POT @ 30 GeV/c

CNGS — OK so far!
1.0e20 POT @ 400 GeV/c

BoosterNB
16.7e20 POT @ 9GeV/c

K2K
1e20 POT @ 12GeV/c

NuMI
12.3e20 POT @ 120GeV/c

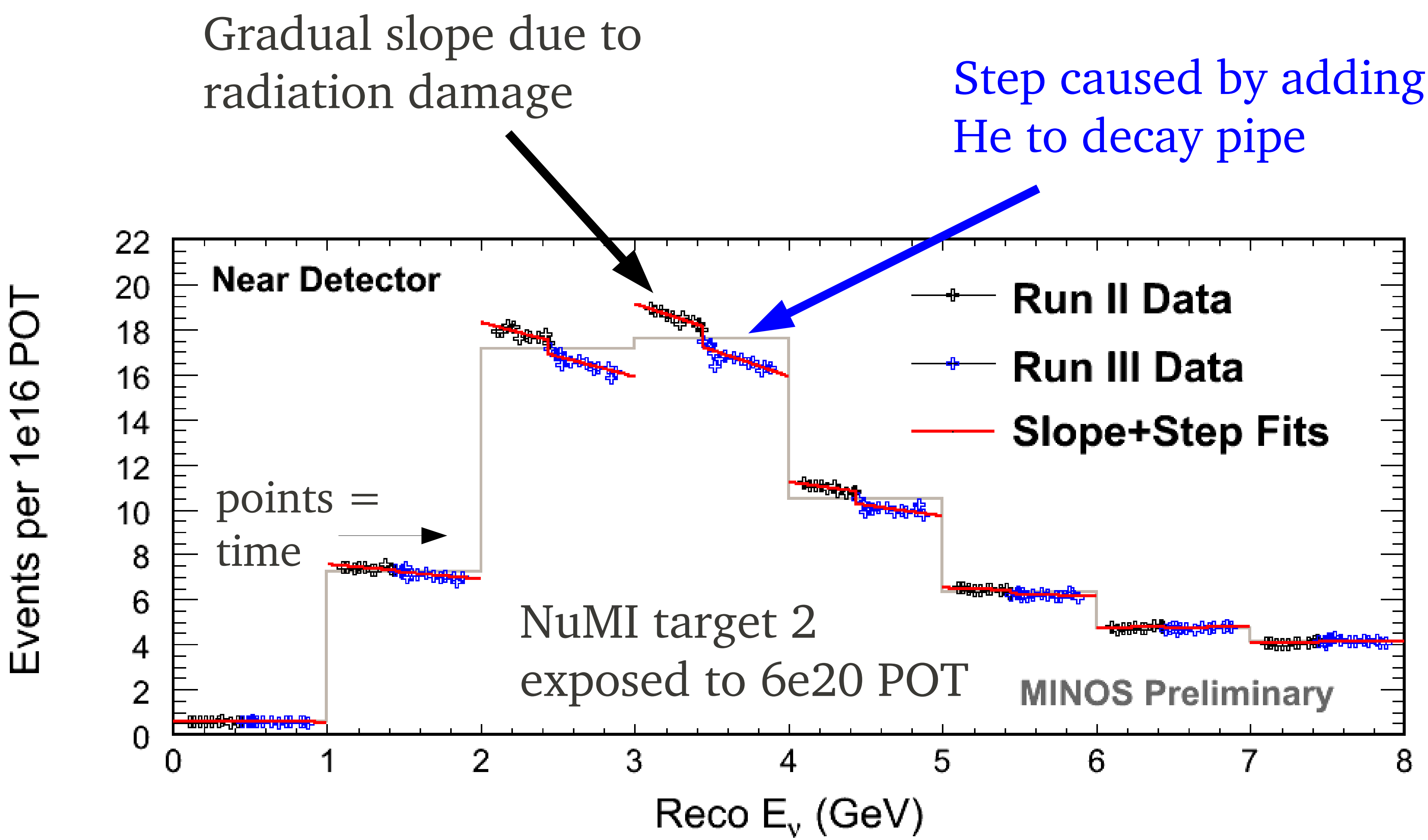
+ *only wounded*

<u>Components encounter:</u>
High radiation, thermal stress, mechanical stress, water leaks

Excess Consumed

- horn
- target
- monitors

Wear and Tear



Muon Neutrino Disappearance

Muon neutrino disappearance

PMNS Mixing Matrix

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

Propagation (vacuum)

flavor mass states

$$|\nu_\alpha(L)\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle \exp(-i L m_j^2 / 2p)$$

(L=distance)

$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 3}|^2 |U_{\mu 1}|^2 \sin^2\Delta_{31} - 4|U_{\mu 3}|^2 |U_{\mu 2}|^2 \sin^2\Delta_{32} - 4|U_{\mu 2}|^2 |U_{\mu 1}|^2 \sin^2\Delta_{21}$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

Characteristic oscillatory behavior depends on Δm^2 and L/E

"Survival Probability"
For a neutrino of energy E a distance L from the source

Muon neutrino disappearance

PMNS Mixing Matrix

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$$\mathbf{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_\mu) = 1 &- 4|U_{\mu 3}|^2|U_{\mu 1}|^2 \sin^2\Delta_{31} \\ &- 4|U_{\mu 3}|^2|U_{\mu 2}|^2 \sin^2\Delta_{32} \\ &- 4|U_{\mu 2}|^2|U_{\mu 1}|^2 \sin^2\Delta_{21} \end{aligned}$$

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Muon neutrino disappearance

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

"Atmospheric oscillations"
L/E~500 km/GeV

Limiting Case

$\theta_{13} = 0$

$|\Delta_{21}| << |\Delta_{31}| \approx |\Delta_{32}|$

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$$\approx 1 - \sin^2 2\theta \, \sin^2(|\Delta m^2| L/4E)$$

$\theta \rightarrow \approx \theta_{23}$

$|\Delta m^2| \rightarrow \approx |\Delta m^2_{32}|$

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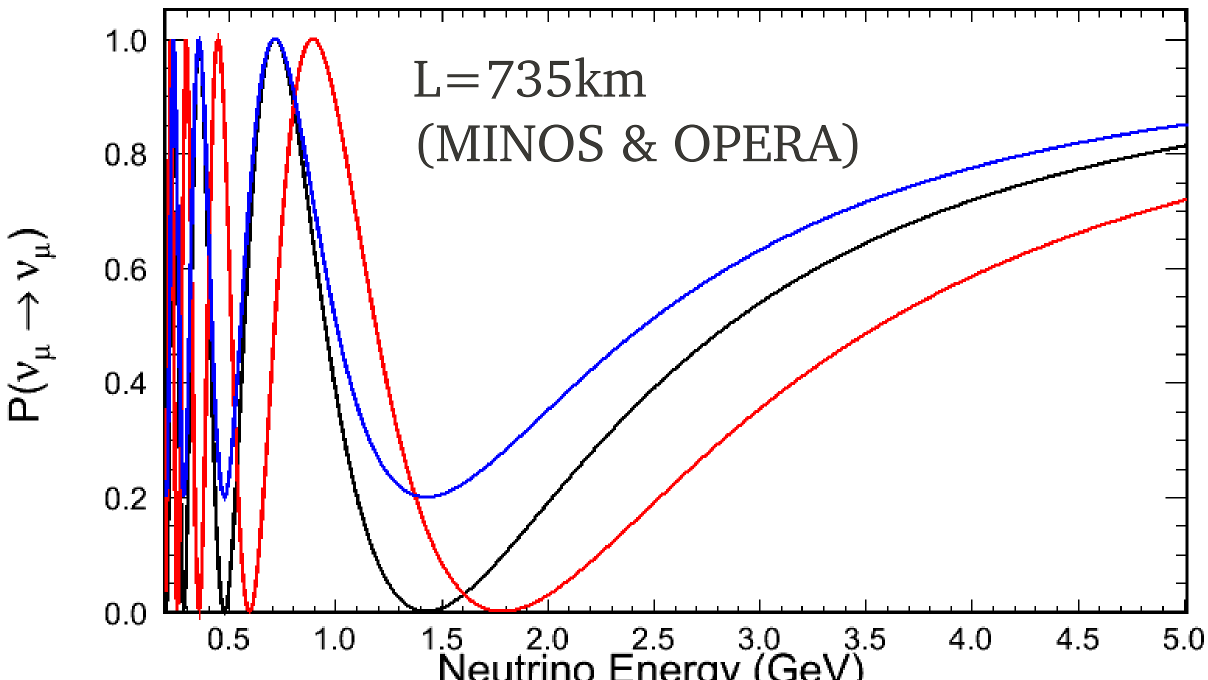
$\theta \approx \theta_{23}$, $|\Delta m^2| \approx |\Delta m^2_{32}|$



$|\Delta m^2| = 2.5\text{x}10^{-3}\ eV^2, \sin^2 2\theta = 0.8$

$|\Delta m^2| = 2.5\text{x}10^{-3}\ eV^2, \sin^2 2\theta = 1.0$

$|\Delta m^2| = 3.0\text{x}10^{-3}\ eV^2, \sin^2 2\theta = 1.0$

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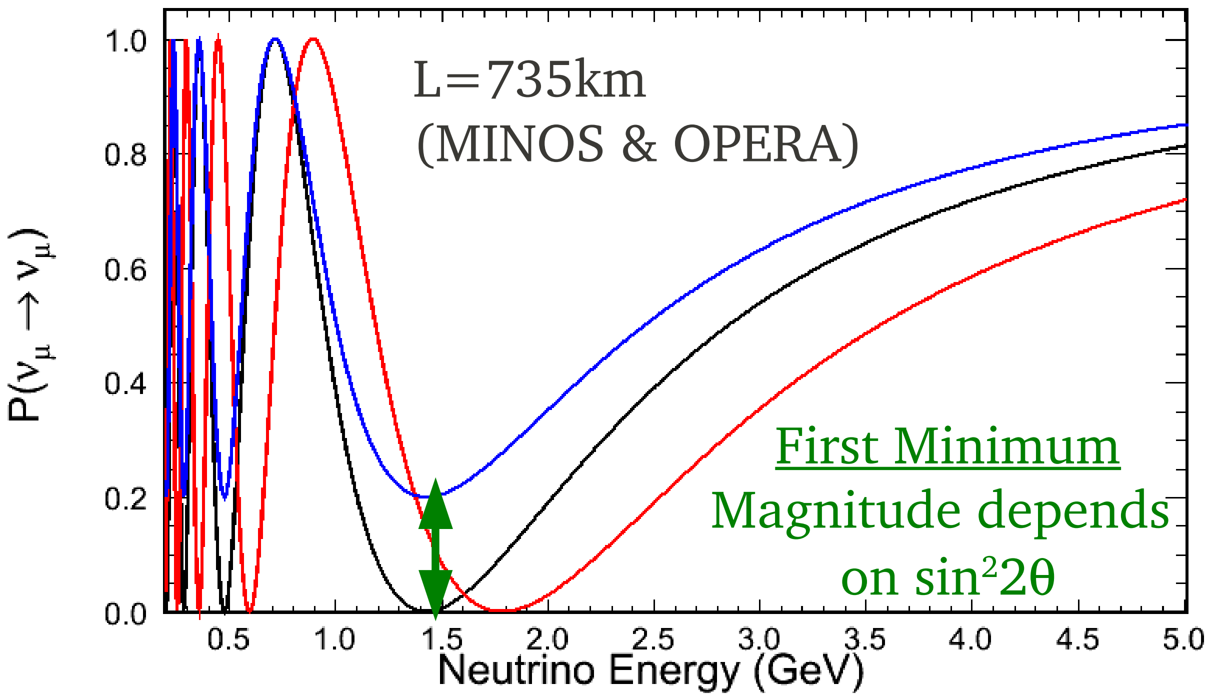
$|\Delta m^2| \to \approx |\Delta m^2_{32}|$

$\theta \to \approx \theta_{23}$



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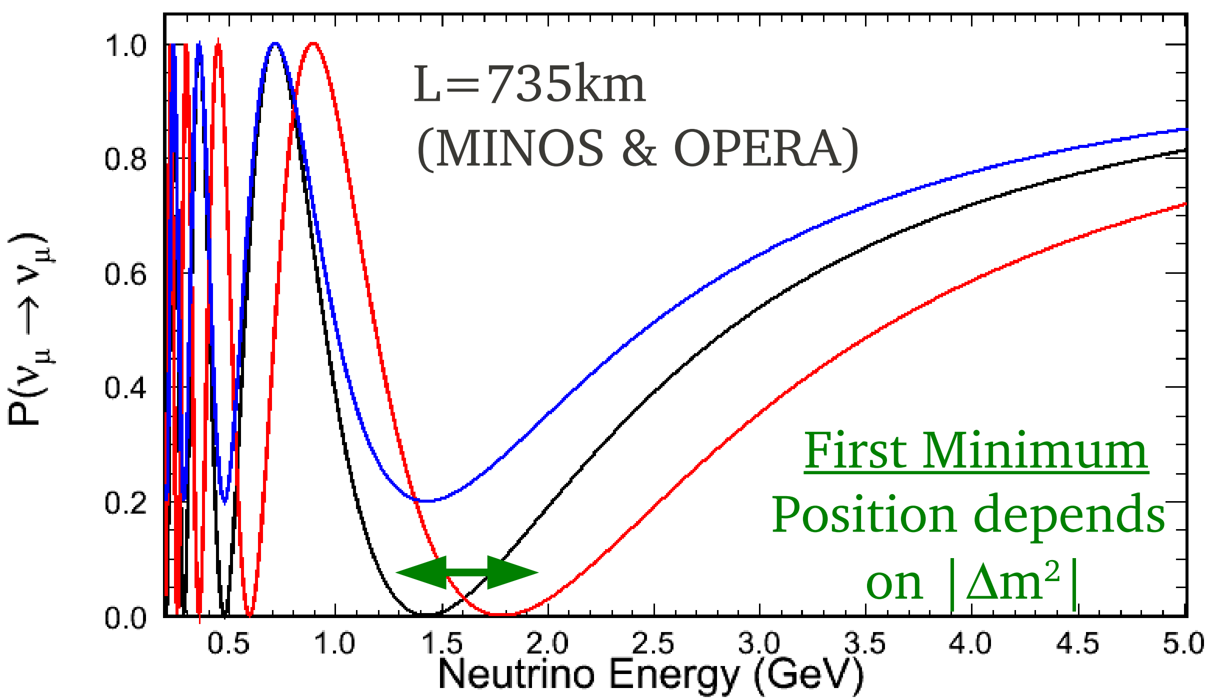

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Challenge: Predict the Far Detector

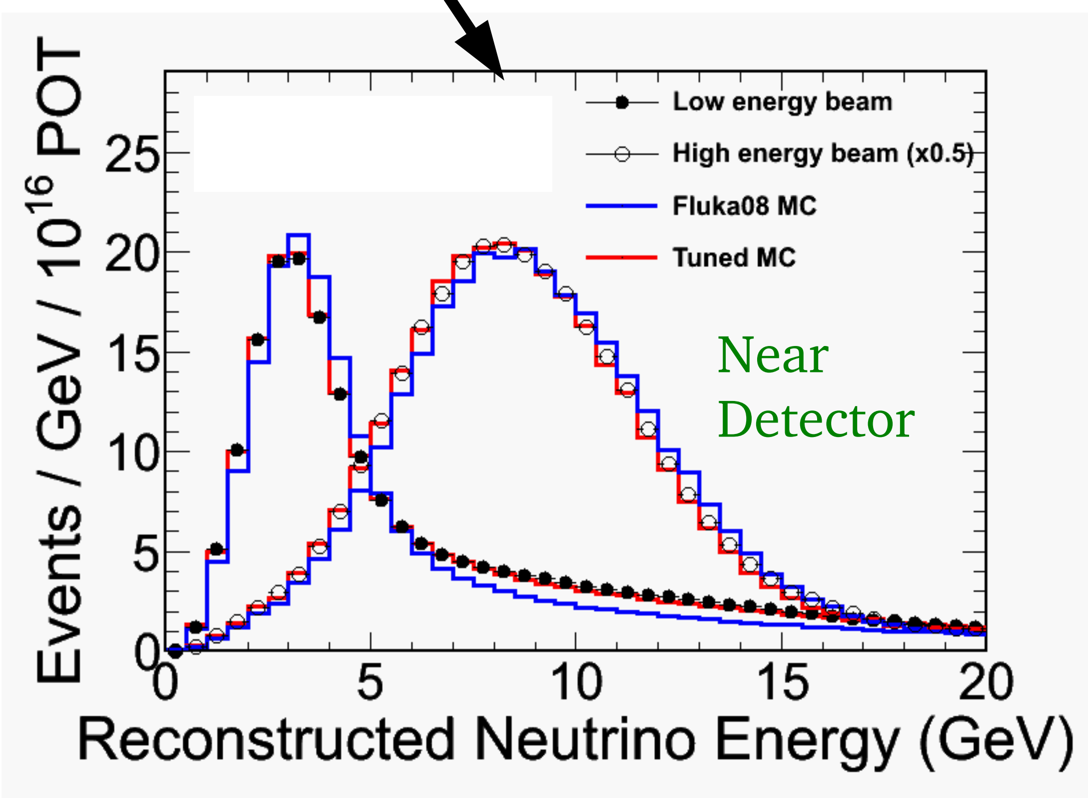
- You want to know neutrino interaction rates as a function of energy for all flavors.
- A priori, $dN/dp_T dp_z$ off your target material for π,K is not known very accurately.
- Your target is thick. Tertiary interactions occur in it, horns, beampipe, etc. Target may wear out over time.
- Your focusing system has uncertainties.
- The weak interaction forces you to use neutrino-nucleus interactions. Significant uncertainties in exclusive and inclusive CC and NC cross-sections for few-GeV E_ν.
- ν_μ,ν_e-CC & NC extrapolate differently.
- Some backgrounds may oscillate.

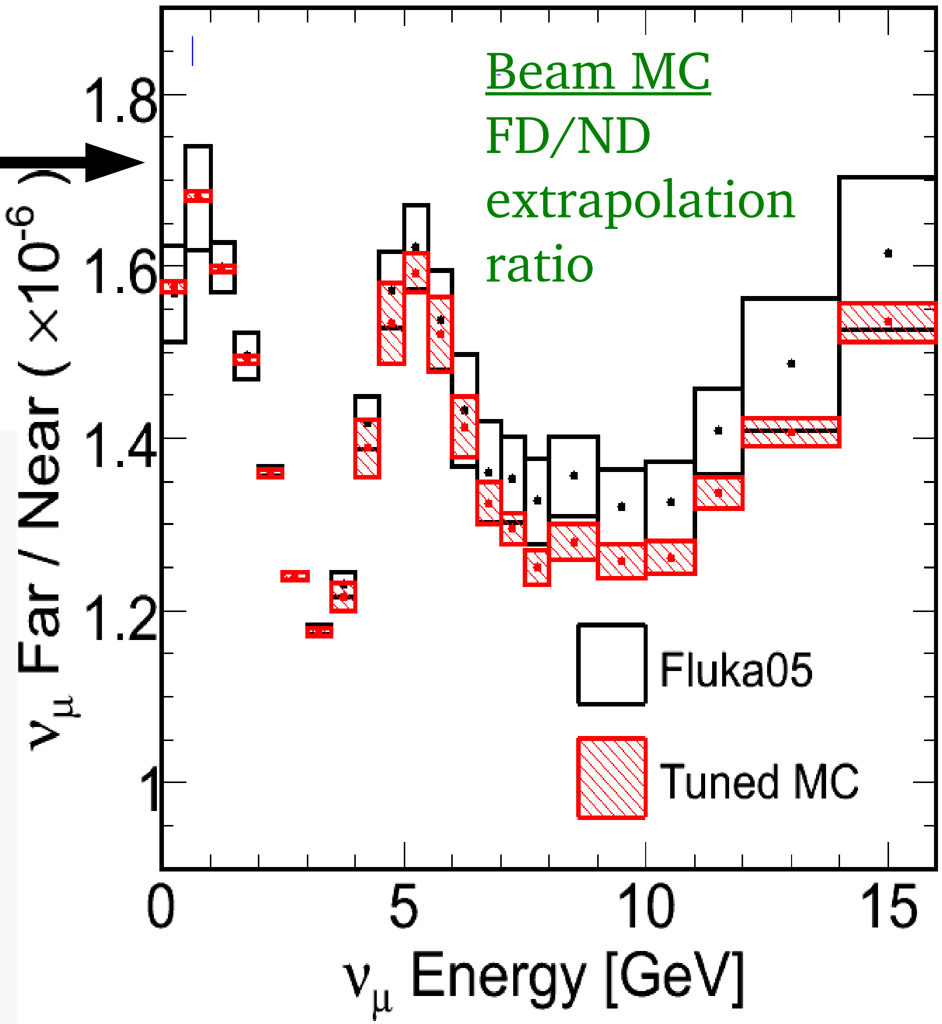
Case study: MINOS $\nu_\mu \rightarrow \nu_\mu$

- MINOS has a ND and a FD made of the same materials and with very similar acceptance
- The ND is used to measure the inclusive ν_μ–CC rate close to the source.
- The ND measurement is corrected for acceptance and impurity using the MC
- It is “extrapolated” to the far detector using a 2 dimensional Near Energy vs. Far Energy Matrix
- This yields a no-oscillations prediction of the ν_μ–CC rate in bins of energy. The prediction is used to correct the FD MC which is then fit to the data.

Case study: MINOS $\nu_\mu \rightarrow \nu_\mu$

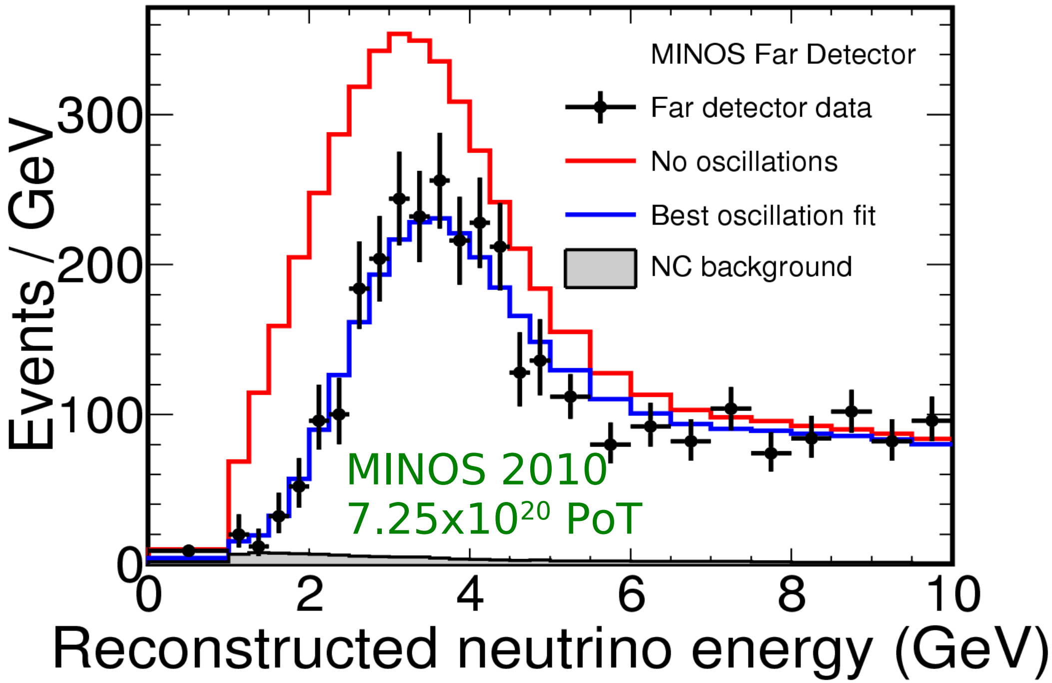
- Extrapolation improved by tuning beam MC to data in multiple focusing configurations

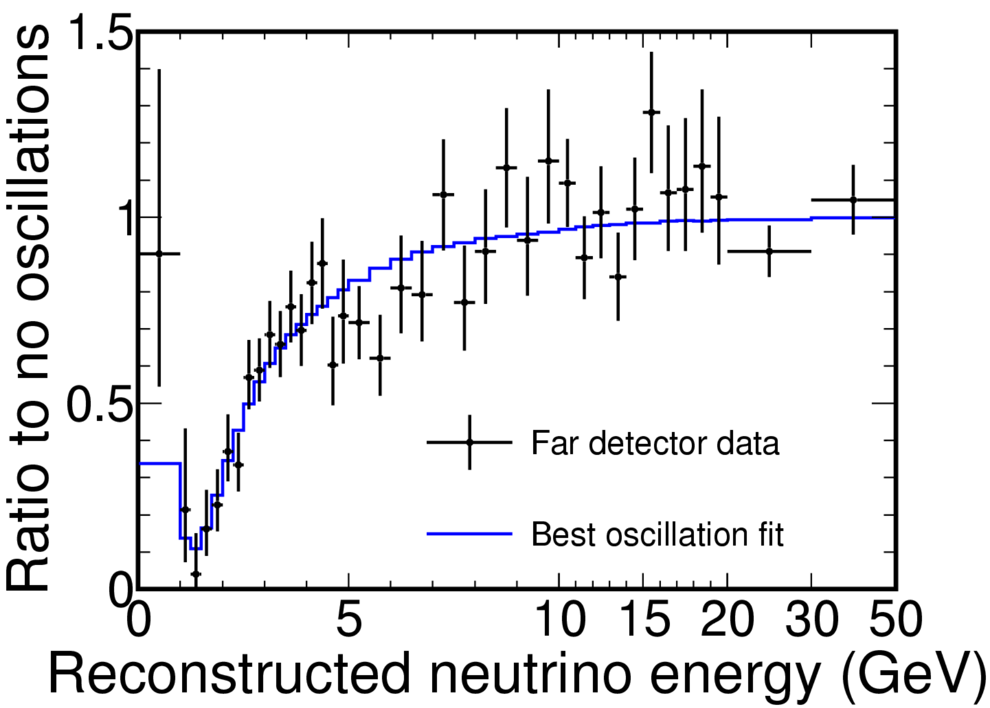




Case study: MINOS $\nu_\mu \rightarrow \nu_\mu$

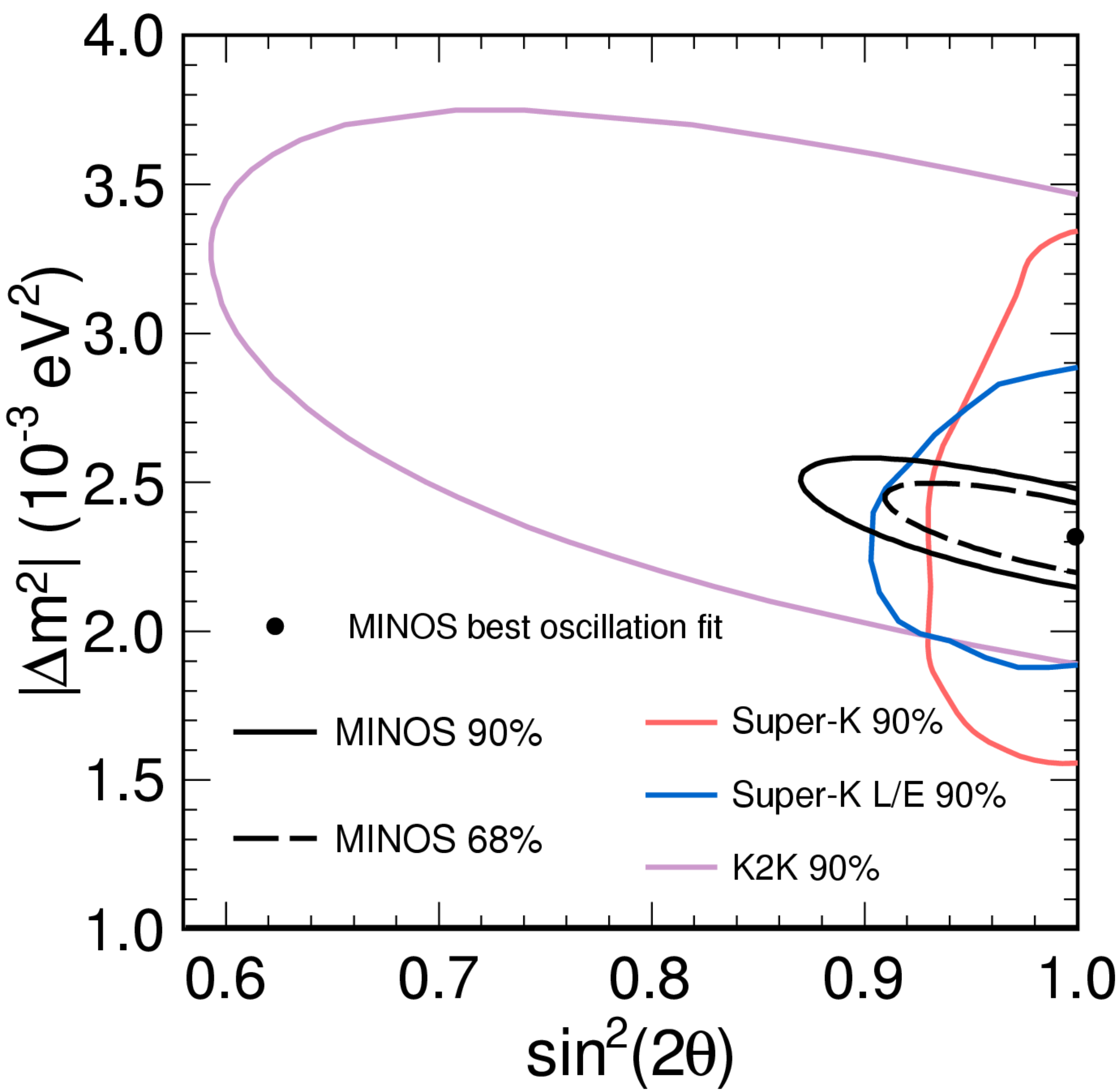
arXiv: 1103.0340v1





- At the FD, events are selected with 88.7% efficiency and 98.3% purity
- Analysis includes interactions inside the FD and muons from interactions in the surrounding rock.
- FD prediction fit to FD data, varying oscillation parameters
- Overall normalization, NC normalization and muon and shower energy scales included as nuisance parameters
- Fit is done in five energy resolution bins, which provides additional sensitivity.

Case study: MINOS $\nu_\mu \rightarrow \nu_\mu$



2010 7.25x10^{20} PoT

Fit result

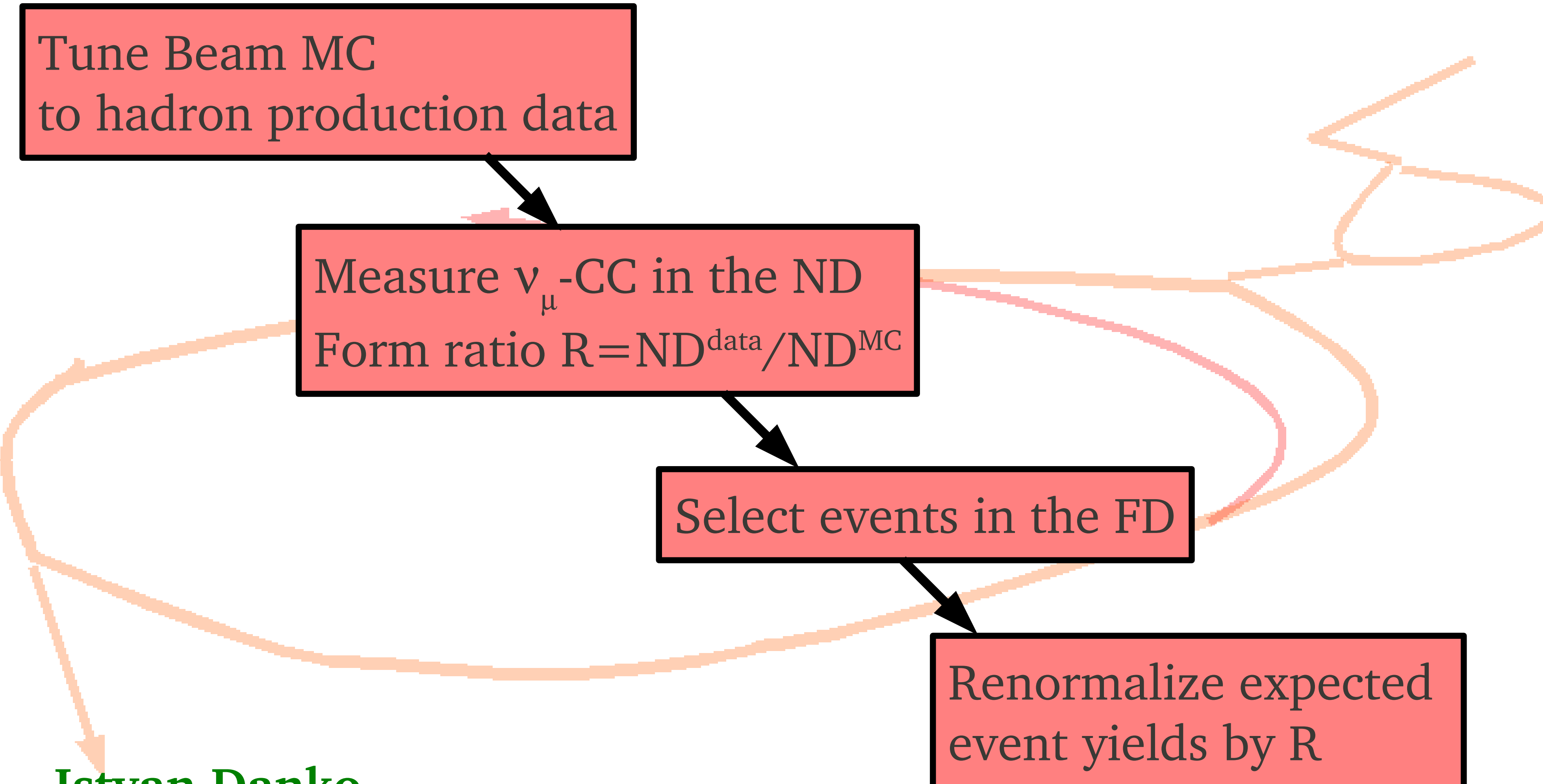
$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3}$ eV^2

$\sin^2 2\theta > 0.90$ (90% CL)

Consistent with maximal mixing.

This is currently the best measurement of $|\Delta m^2|$ and the best accelerator measurement of $\sin^2 2\theta$

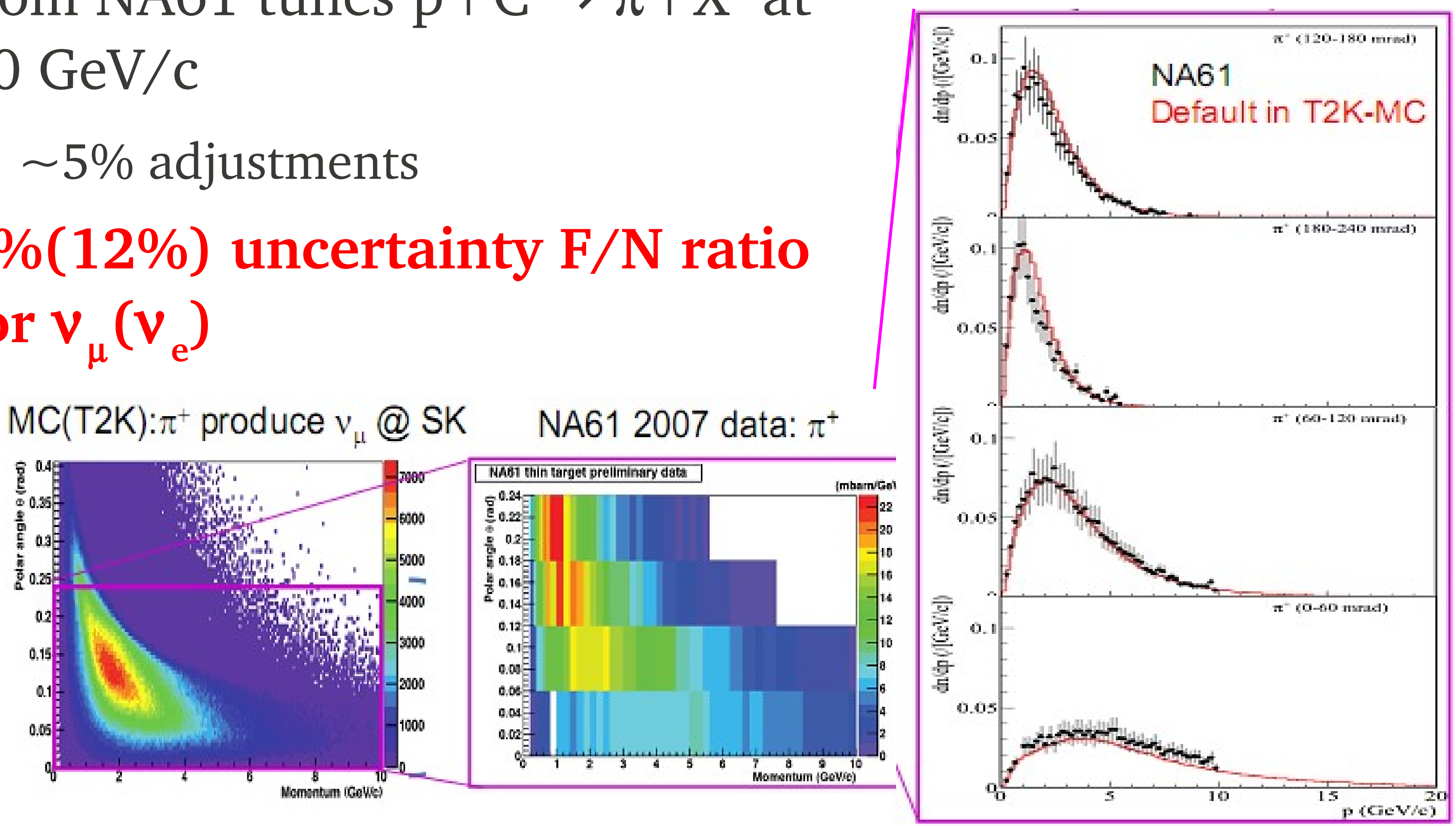
Case Study: T2K

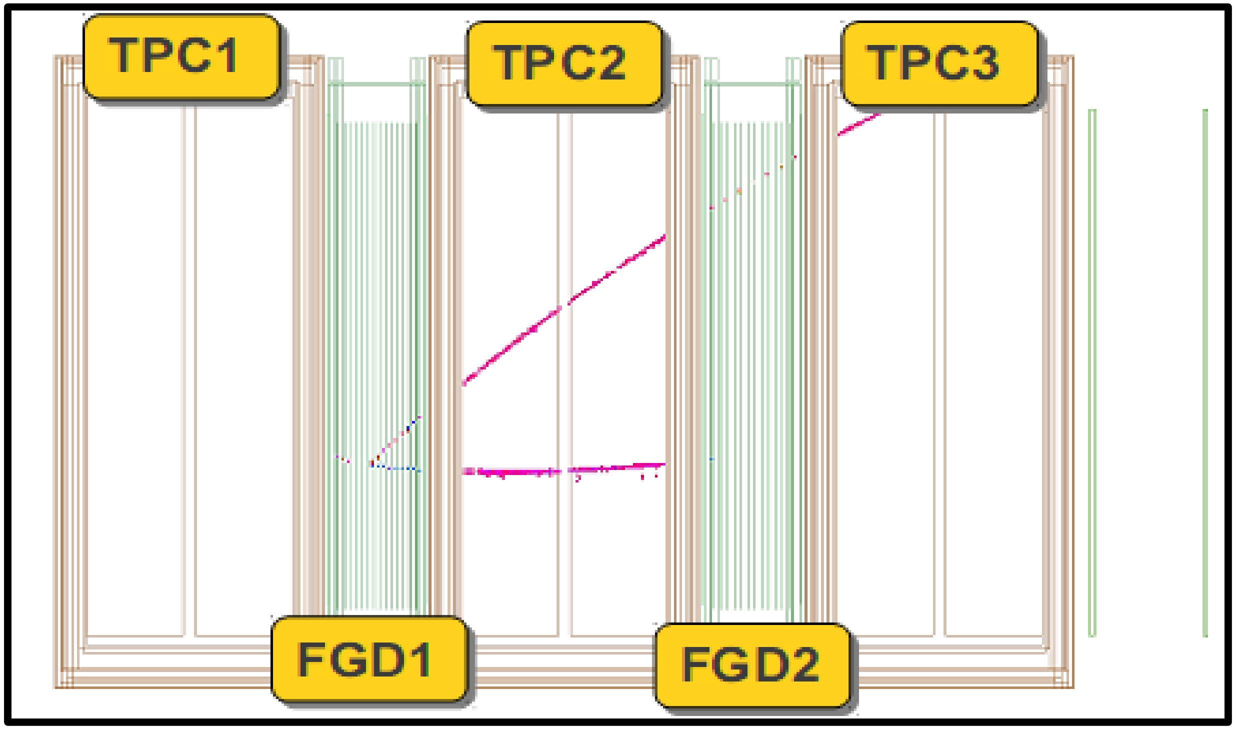


Istvan Danko,
March 22, 2011
at FNAL

Case Study: T2K

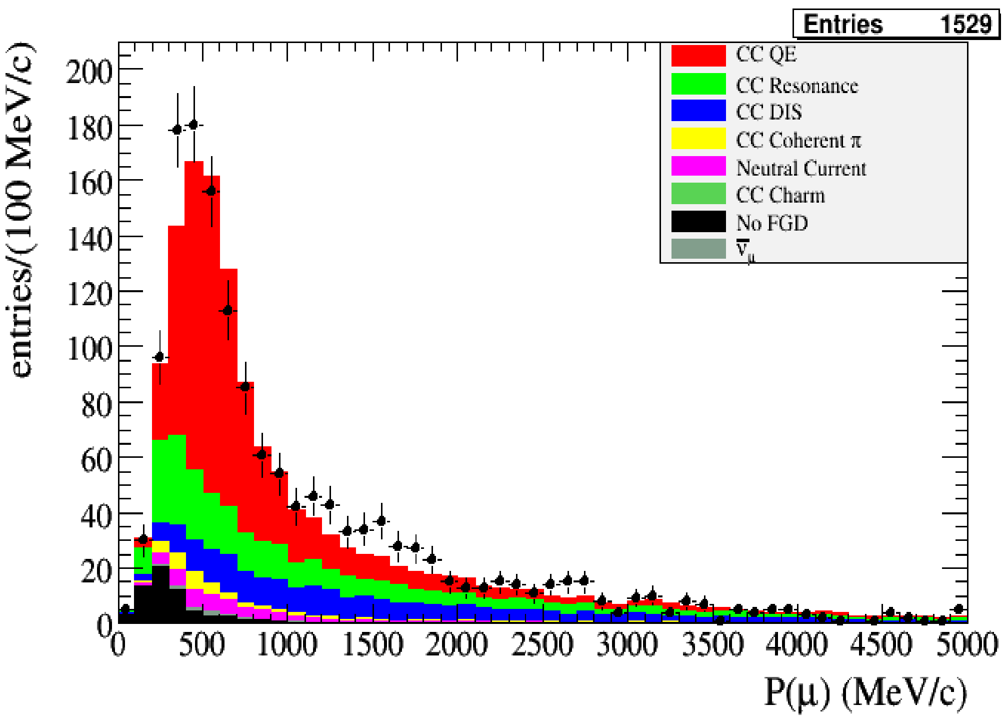
- External hadron production data from NA61 tunes p+C → π+X at 30 GeV/c
  - ~5% adjustments
- **7%(12%) uncertainty F/N ratio for $\nu_\mu (\nu_e)$**





Case Study: T2K

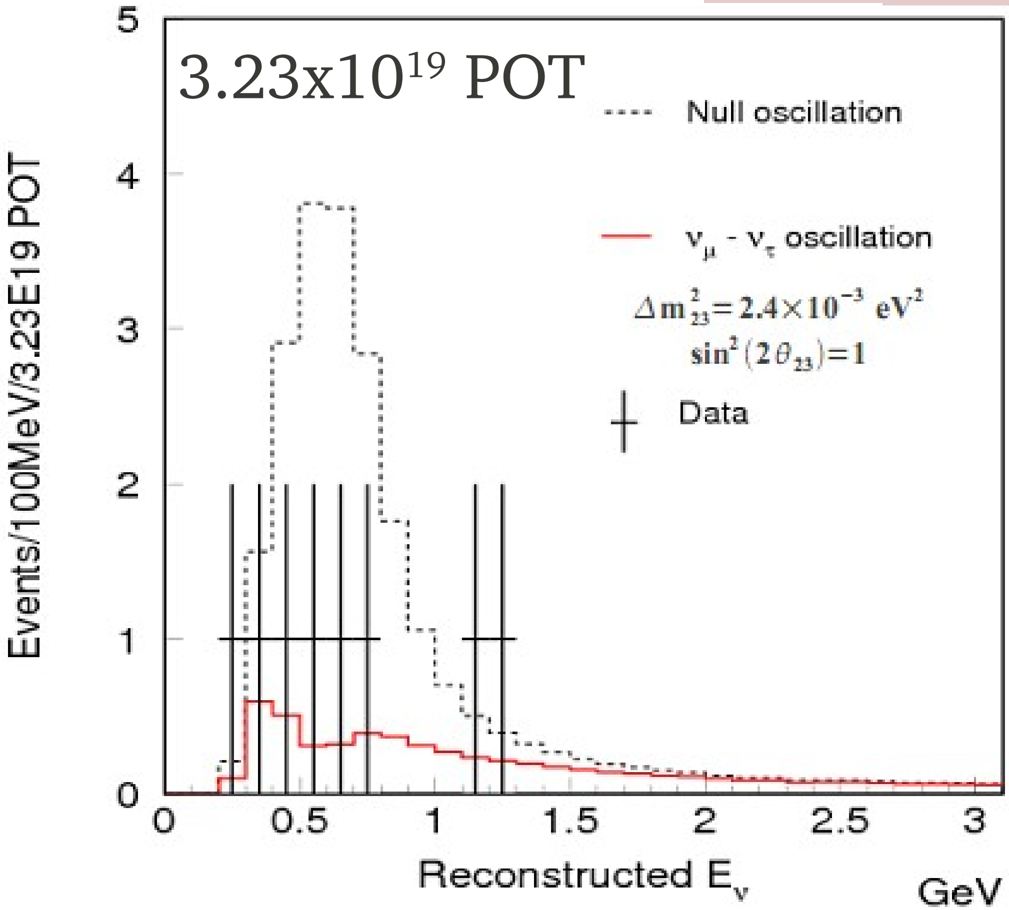
Use of the Near Detector



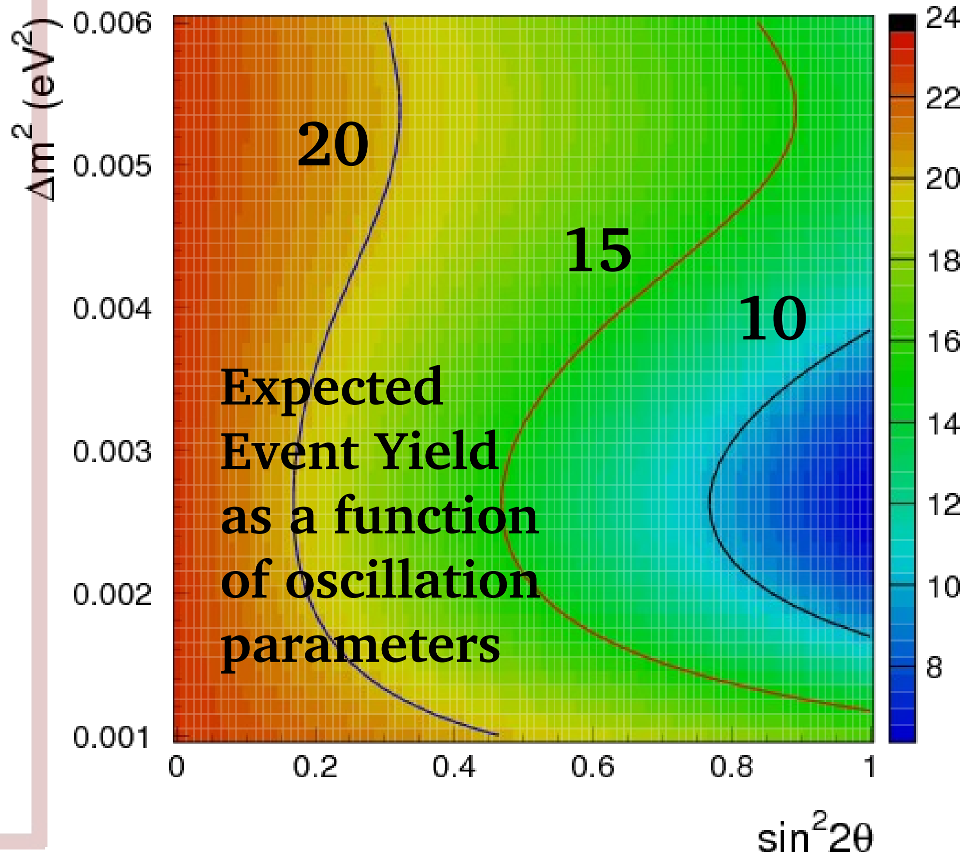
- Inclusive ν_μ-CC measured in the ND280.
- Currently used to renormalize FD prediction
- $N_{data}/N_{MC} = 1.06 \pm 0.06$
- Future analyses will use spectrum, tune MC, etc.

Case Study: T2K

Far Detector Super-K



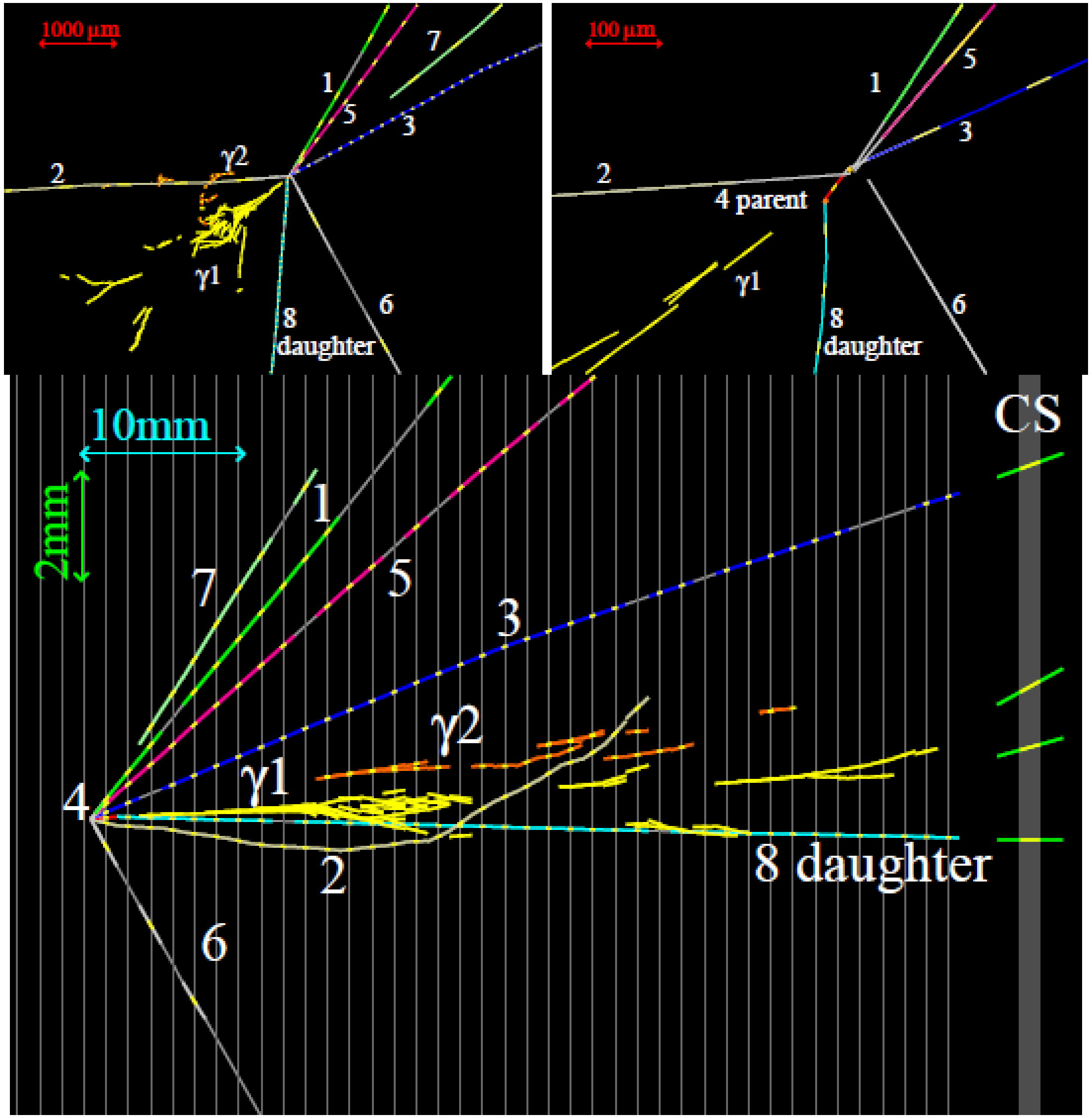
- 8 ν_μ-CC observed in FD
- Consistent with parameters measured by MINOS/SK



Additional Details:
J. Imber – J8 D. Ruterbories – J8
K. Gilje, G. Lopez - J8

OPERA: Search for $\nu_\mu \rightarrow \nu_\tau$

- The bulk of disappearing ν_μ at 735km have energies below τ threshold
- τ are difficult to detect
  - $c\tau = 87\mu m$
  - decay to a variety of final states.
- Exposure of 1.89×10^{19}POT
  - Expect 0.56 ± 0.13 τ events
  - Expect 0.018 ± 0.007 background
- **One candidate observed!**
- Full run 22.5×10^{20}POT, expect 10 ν_τ and <1 background



Electron Neutrino

Appearance

Electron Neutrino Appearance

"Atmospheric oscillations"
L/E~500 km/GeV

$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}} \right|^2$$

"Atmospheric" Term

$$\sqrt{P_{atm}} = \sin(\theta_{23}) \sin(2\theta_{13}) \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31}$$

depends on Δm^2_{31}
and unknown θ_{13}

"Solar" Term

$$\sqrt{P_{sol}} = \cos(\theta_{23}) \sin(2\theta_{12}) \frac{\sin(aL)}{(aL)} \Delta_{21}$$

<1% effect for current
accelerator experiments

Electron Neutrino Appearance

"Atmospheric oscillations"
L/E~500 km/GeV

$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}} \right|^2$$

"Solar" Term

$$\sqrt{P_{sol}} = \cos(\theta_{23}) \sin(2\theta_{12}) \frac{\sin(aL)}{(aL)} \Delta_{21}$$

"Atmospheric" Term

$$\sqrt{P_{atm}} = \sin(\theta_{23}) \sin(2\theta_{13}) \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31}$$

<1% effect for current accelerator experiments

depends on Δm^2_{31} and unknown θ_{13}

L/E oscillatory behavior embedded in Δ_{ij} terms

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

Electron Neutrino Appearance

"Atmospheric oscillations"
L/E~500 km/GeV

$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}}\, e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}} \right|^2$$

"Solar" Term

$$\sqrt{P_{sol}} = \cos(\theta_{23}) \sin(2\theta_{12}) \frac{\sin(aL)}{(aL)} \Delta_{21}$$

<1% effect for current accelerator experiments

"Atmospheric" Term

$$\sqrt{P_{atm}} = \sin(\theta_{23}) \sin(2\theta_{13}) \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31}$$

depends on Δm^2_{31}
and unknown θ_{13}

Matter Effect

Additional term in Hamiltonian introduced by ν_e+e and $\bar{\nu}_e$+e CC scattering modifies oscillations

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

Positive for neutrinos
Negative for anti-neutrinos

$$a = \frac{\pm G_F N_e}{\sqrt{2}} \approx \frac{1}{4000\,km}$$

Electron Neutrino Appearance

"Atmospheric oscillations"
L/E~500 km/GeV

"Solar" Term

$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}}\, e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}} \right|^2$$

$$\sqrt{P_{sol}} = \cos(\theta_{23}) \sin(2\theta_{12}) \frac{\sin(aL)}{(aL)} \Delta_{21}$$

<1% effect for current accelerator experiments

"Atmospheric" Term

$$\sqrt{P_{atm}} = \sin(\theta_{23}) \sin(2\theta_{13}) \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31}$$

depends on Δm^2_{31} and unknown θ_{13}

CP Violating Phase

$+\delta$ for neutrinos

$-\delta$ for anti-neutrinos

Electron Neutrino Appearance

"Atmospheric oscillations"
L/E~500 km/GeV

"Solar" Term

$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}} \right|^2$$

$$\sqrt{P_{sol}} = \cos(\theta_{23}) \sin(2\theta_{12}) \frac{\sin(aL)}{(aL)} \Delta_{21}$$

"Atmospheric" Term

$$\sqrt{P_{atm}} = \sin(\theta_{23}) \sin(2\theta_{13}) \frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)} \Delta_{31}$$

<1% effect for current accelerator experiments

depends on Δm^2_{31} and unknown θ_{13}

Mass Hierarchy
Unknown sign of Δm^2_{31} & Δm^2_{32} modifies probabilities

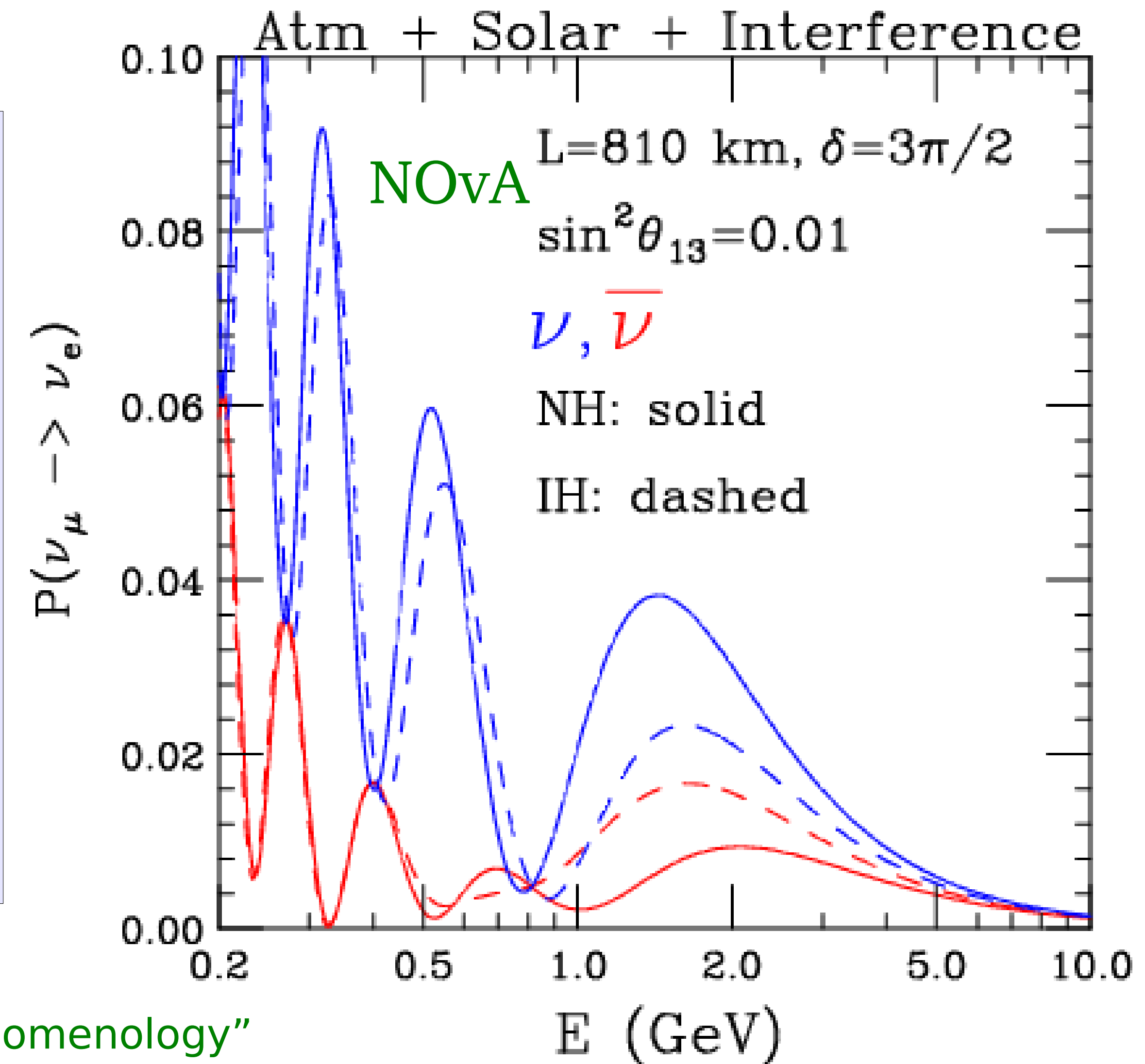
Electron Neutrino Appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}} \right|^2$$

$$\sqrt{P_{atm}} = \sin(\theta_{23}) \sin(2\theta_{13}) \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31}$$

$$\sqrt{P_{sol}} = \cos(\theta_{23}) \sin(2\theta_{12}) \frac{\sin(aL)}{(aL)} \Delta_{21}$$

$$a = \frac{\pm G_F N_e}{\sqrt{2}} \approx \frac{1}{4000\,km}$$

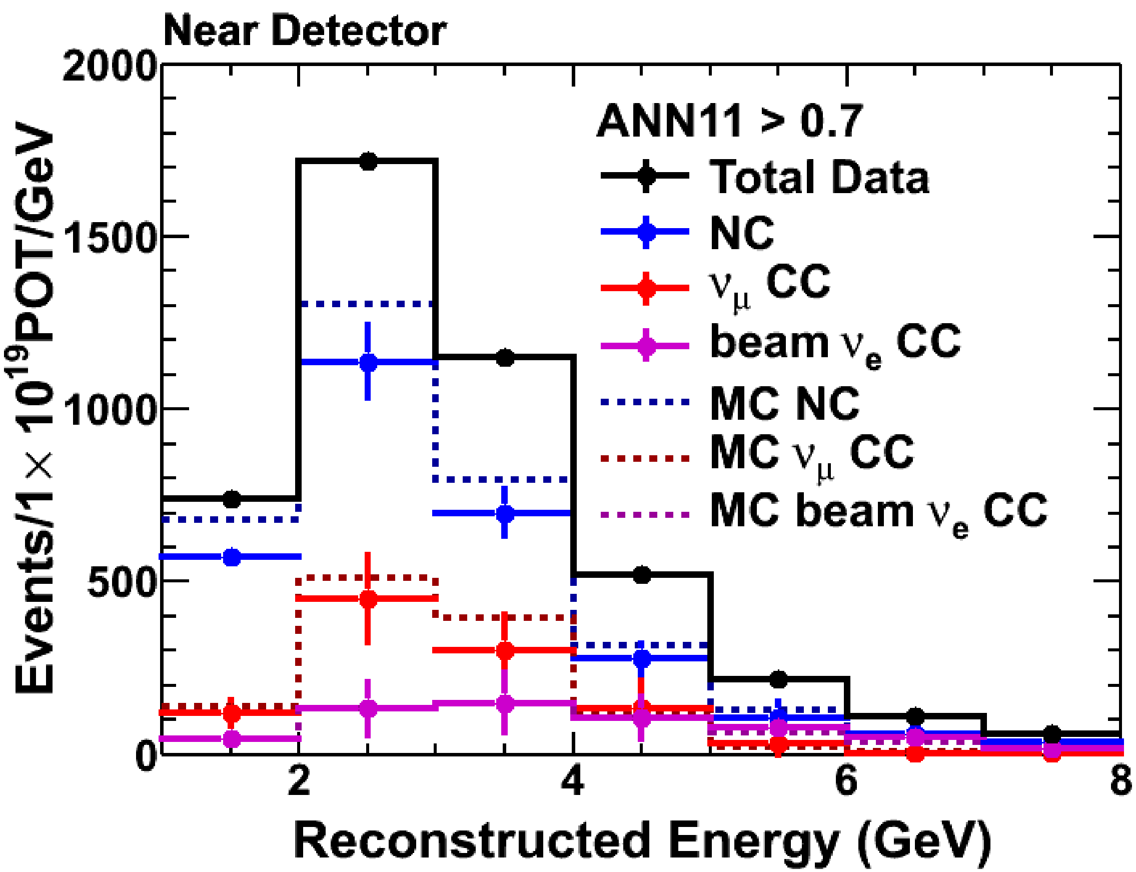


S. Parke, "Neutrino Oscillation Phenomenology" in *Neutrino Oscillations: Present Status and Future Plans,* Ed. J. Thomas, P. Vahle

MINOS $\nu_\mu \rightarrow \nu_e$

Phys. Rev. D 82, 051102(R) (2010)

- Selection of ν_e-CC interactions and rejection of NC and ν_μ-CC interactions
  - 11 topological quantities and a neural network are used to produce a discriminating variable
  - Validated against data using:
    - ν_μ-CC where the μ is removed
    - ν_μ-CC where the μ is replaced with a simulated electron
    - test beam electrons



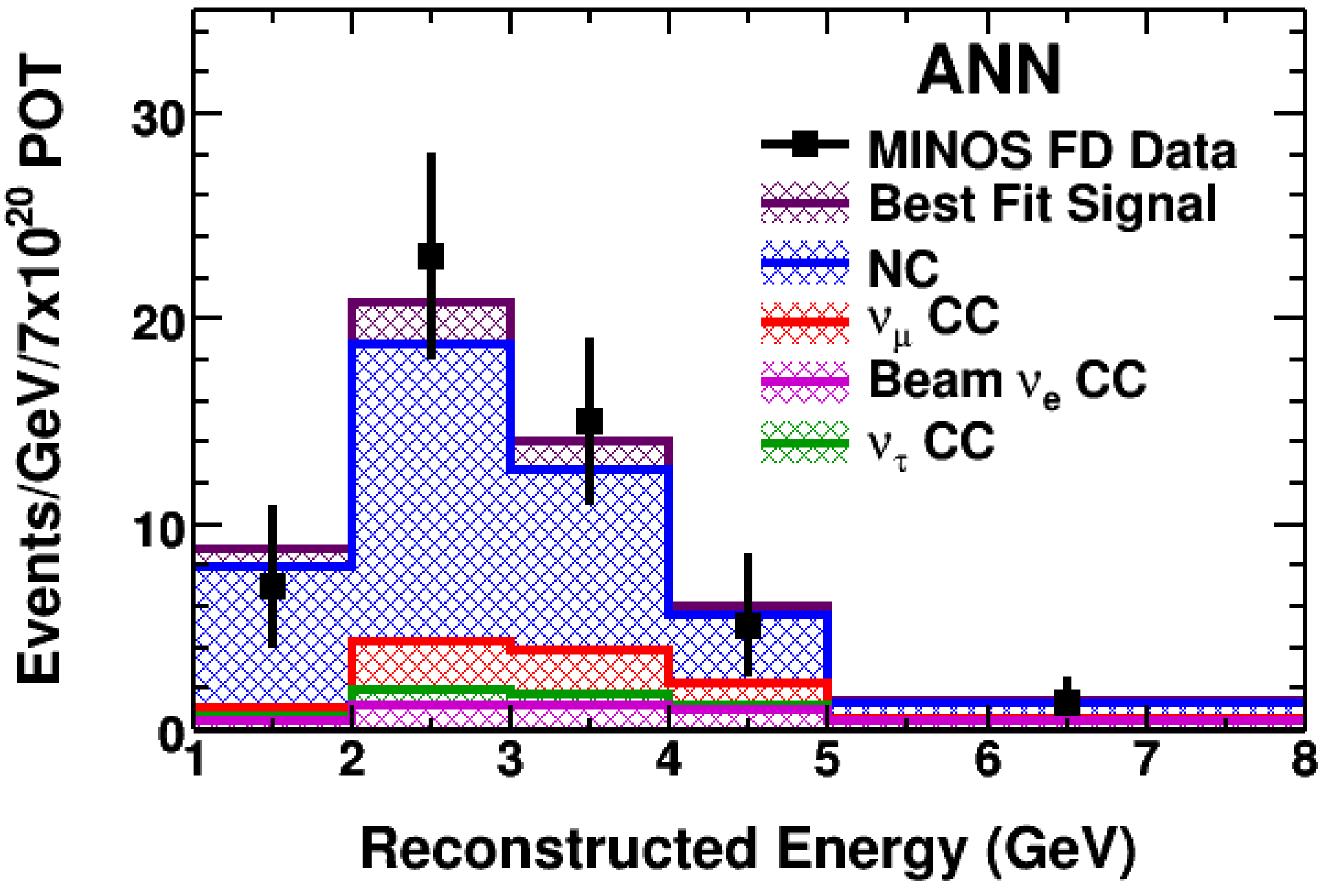
- NC,ν_e, ν_μ-CC extrapolate to FD differently and ν_μ also oscillate
  - Three beam energy configurations, each with different background compositions are used to measure/constrain the compositions.

MINOS $\nu_\mu \rightarrow \nu_e$

Phys. Rev. D 82, 051102(R) (2010)

Far Detector

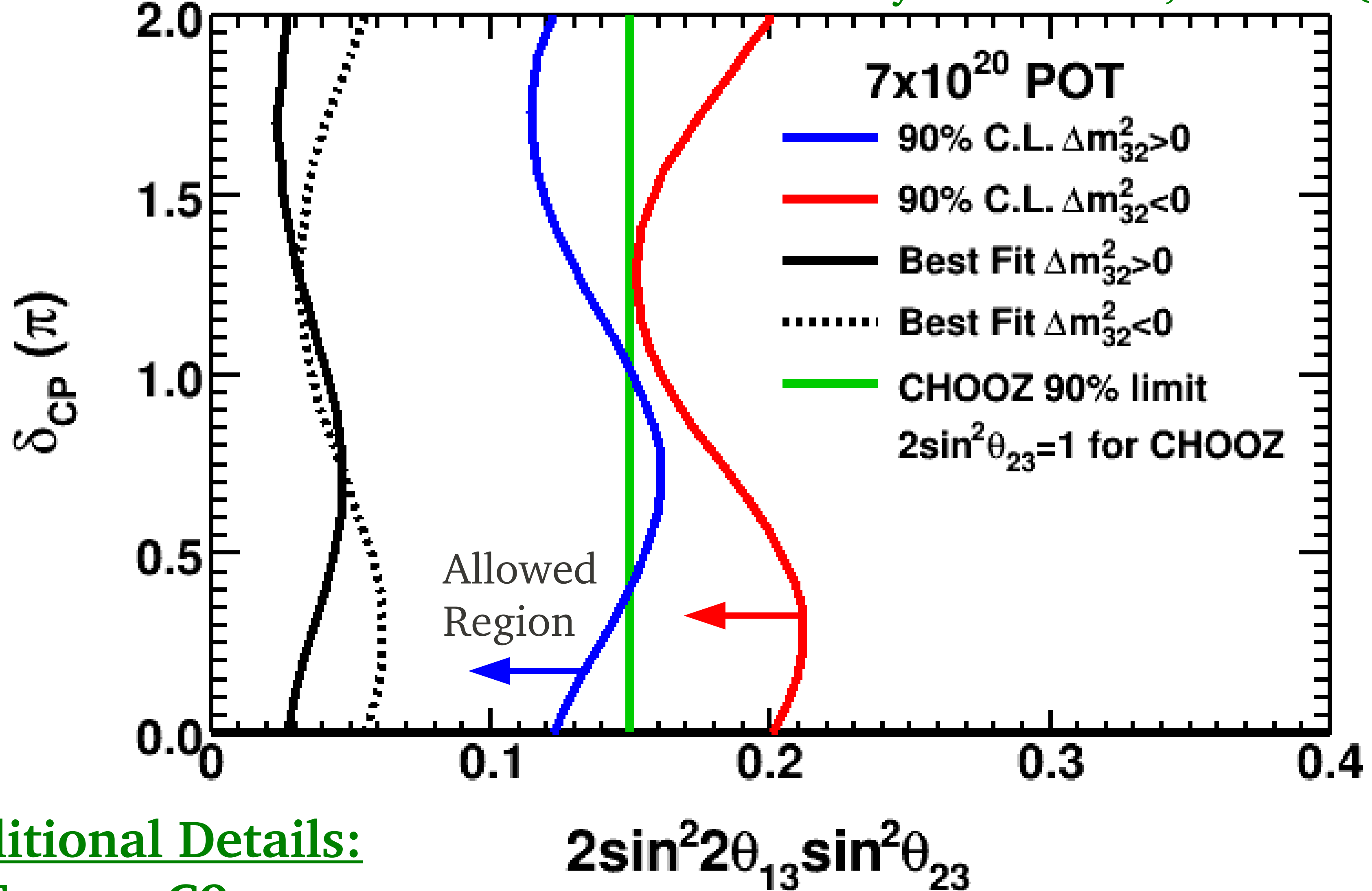
Expected Background: 49.1 ± 7.0(stat) ± 2.7(syst)



54 events observed

MINOS $\nu_\mu \rightarrow \nu_e$

Phys. Rev. D 82, 051102(R) (2010)



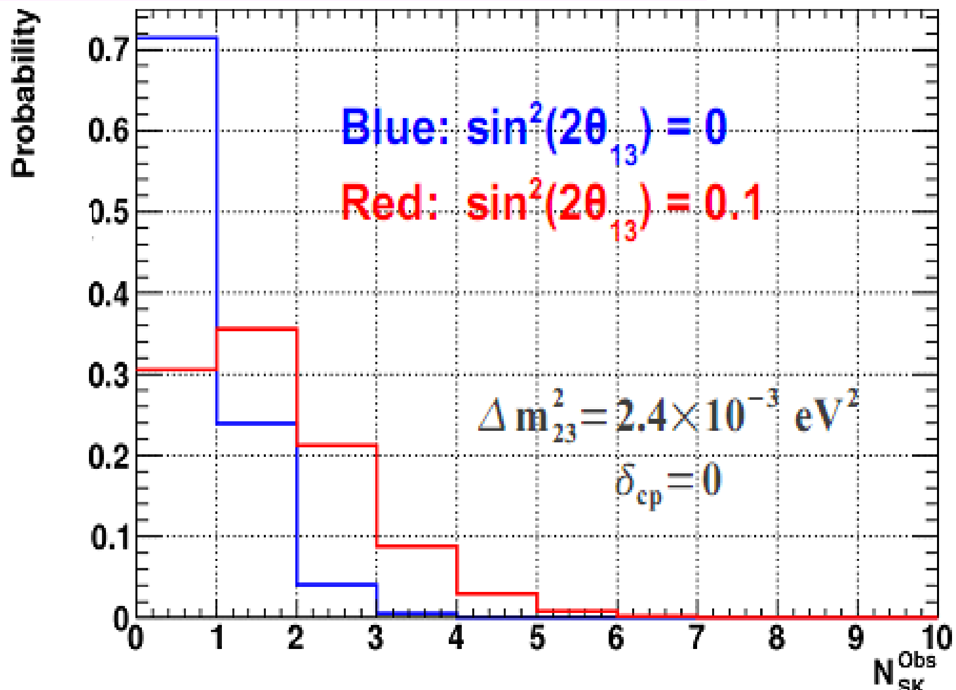
Additional Details:

R. Toner - C9

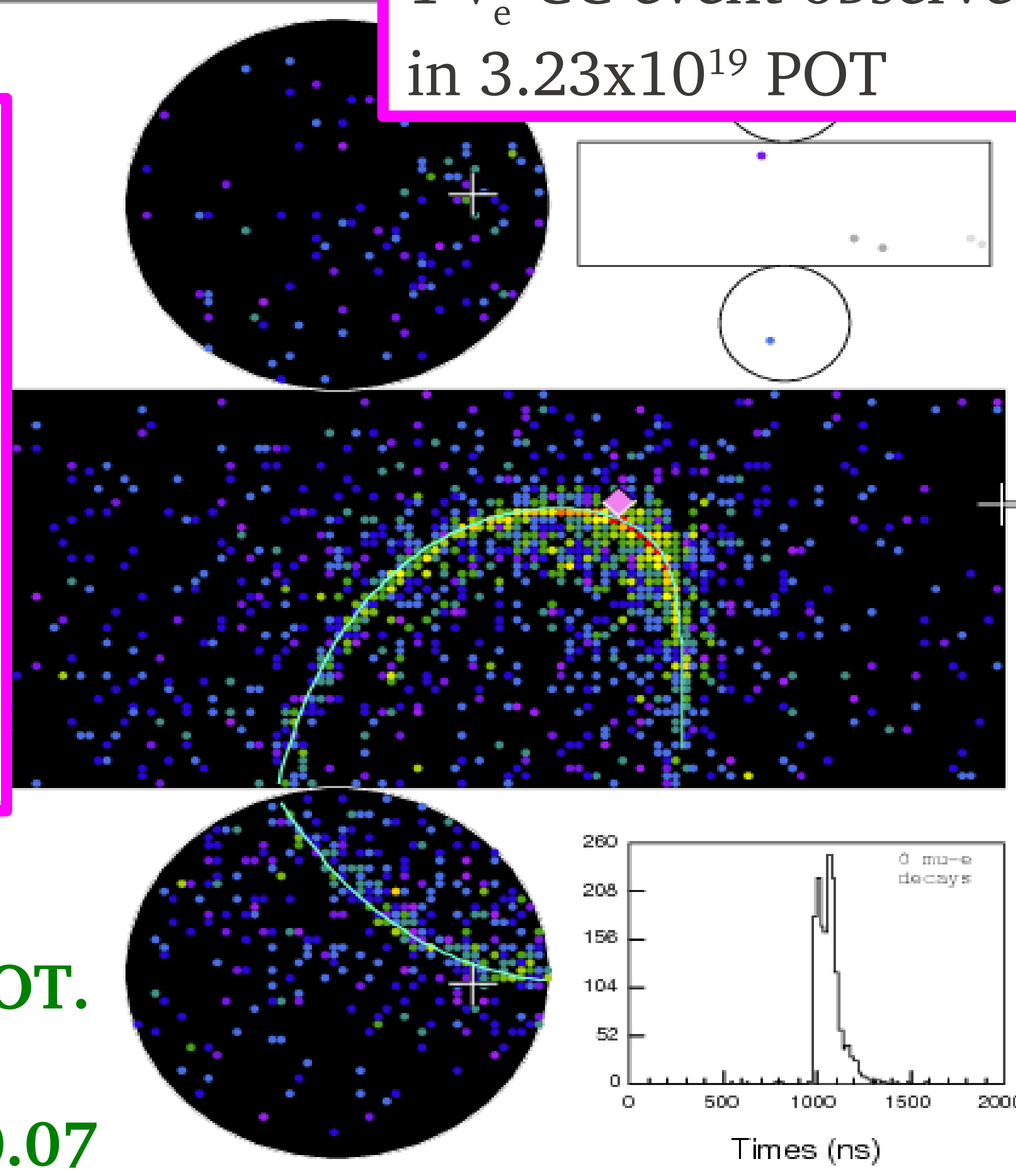
S. Budd - C9

T2K: ν_e-event!

Probability of observing N ν_e-CC events at SK

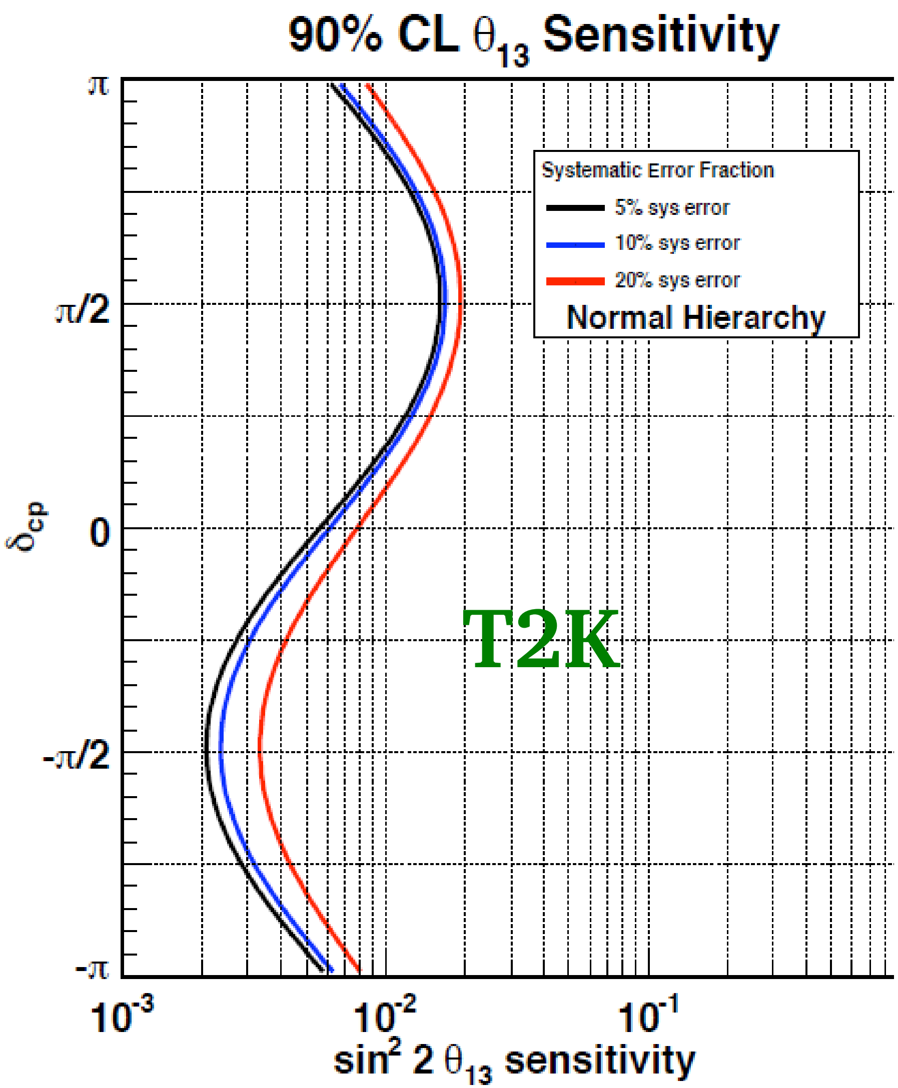


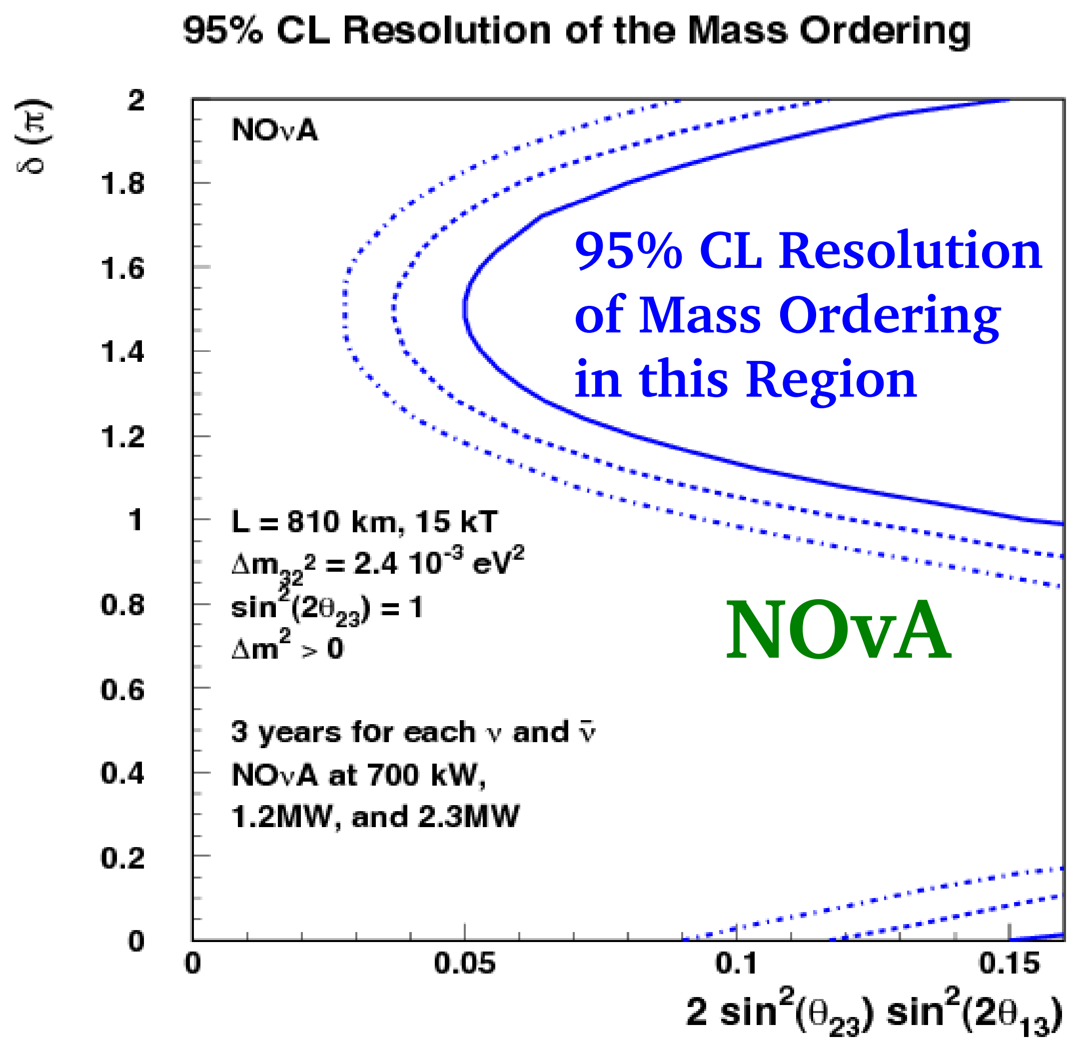
1 ν_e-CC event observed in 3.23×10^{19} POT



T2K has accumulated 1.45×10^{20} POT. For that exposure, the expected 90% CL sensitivity is at $\sin^2 2\theta_{13} \approx 0.07$

Projected sensitivity of T2K and NOvA





Alena Gavrilenko

Additional Details
A. Gavrilenko – C9
M. Betancourt – R7

Anti-ν_μ disappearance

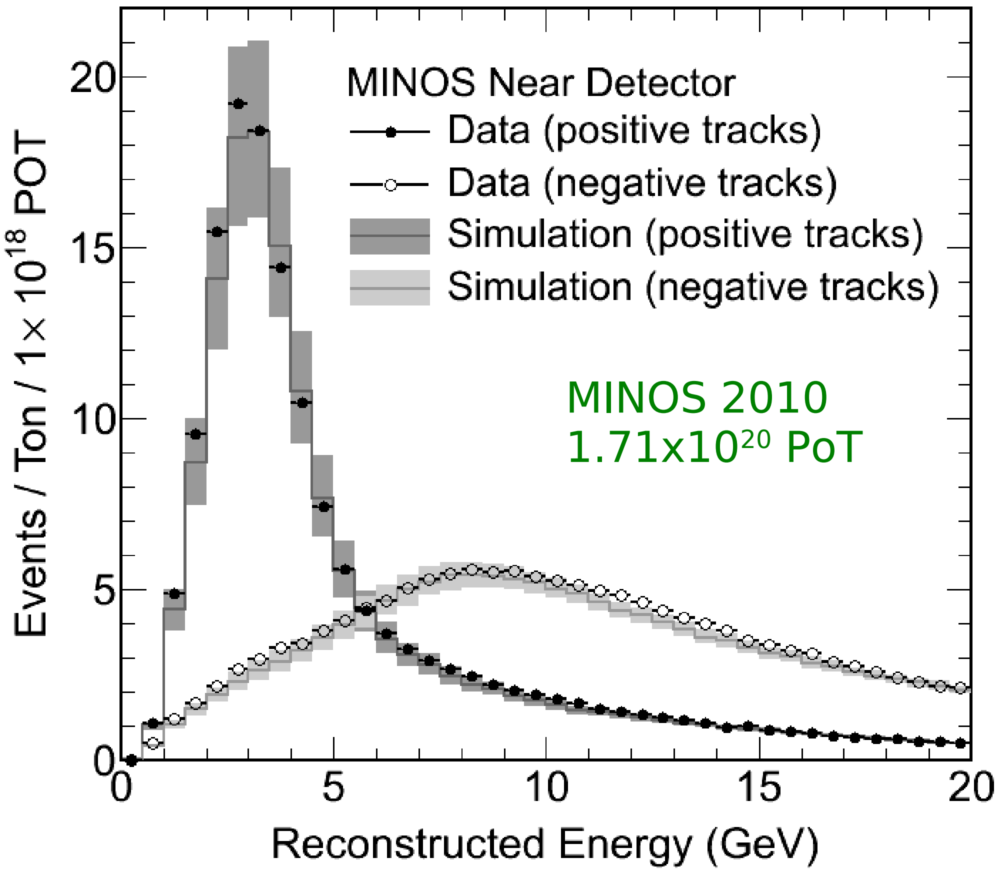
Anti-ν_μ disappearance

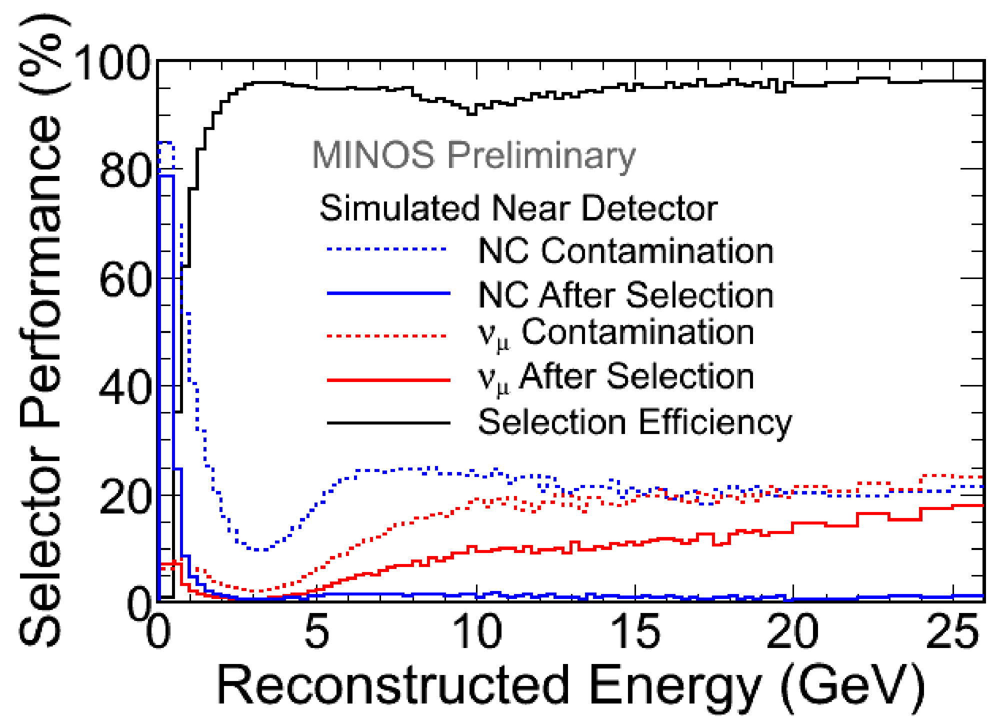
- Studying oscillations with a neutrino beam is more profitable than an anti-neutrino beam
  - larger cross-section for neutrinos (x2.5)
  - more π^+ than π^- produced at the target (~ +10%)
- CPT requires $P(\nu_\mu \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ in vacuum
- But, the earth isn't a vacuum, and new physics could modify the oscillation probabilities
- Neutrinos have surprised us before and may do so again.
- MINOS has studied this in two ways:
  - Using a $\bar{\nu}_\mu$-optimized beam
  - Using $\bar{\nu}_\mu$ in a ν_μ-optimized beam

Anti-ν_μ disappearance

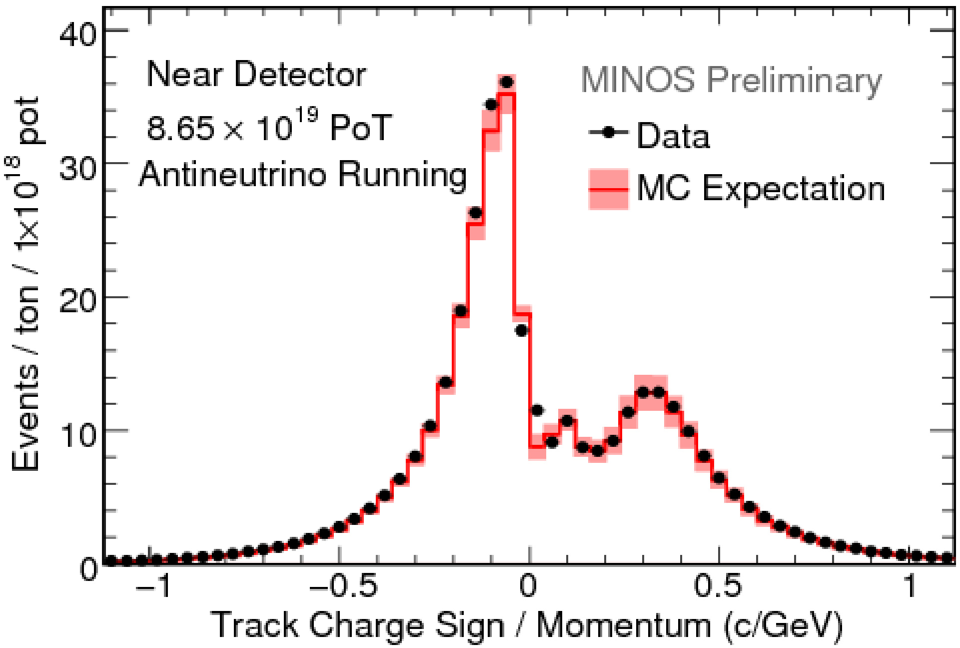
Using a $\bar{\nu}_\mu$-optimized beam

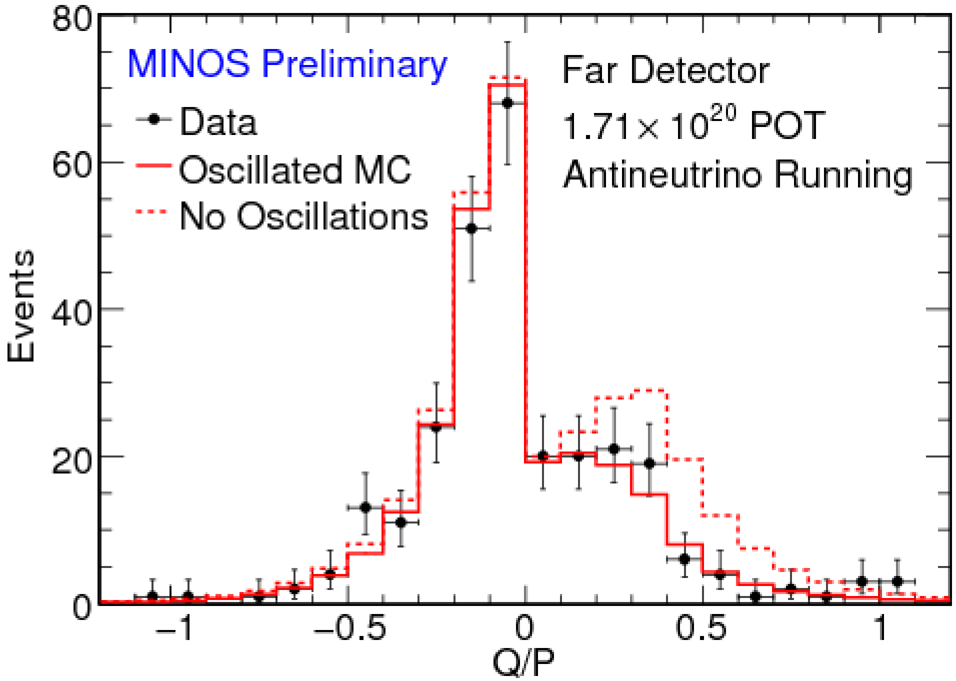
arXiv 1104.0333





- Analysis is similar to ν_μ disappearance. Same reconstruction & event selection, with reversed B-field.
- Most significant difference is larger wrong-sign component. But, it's measured in magnetized ND.





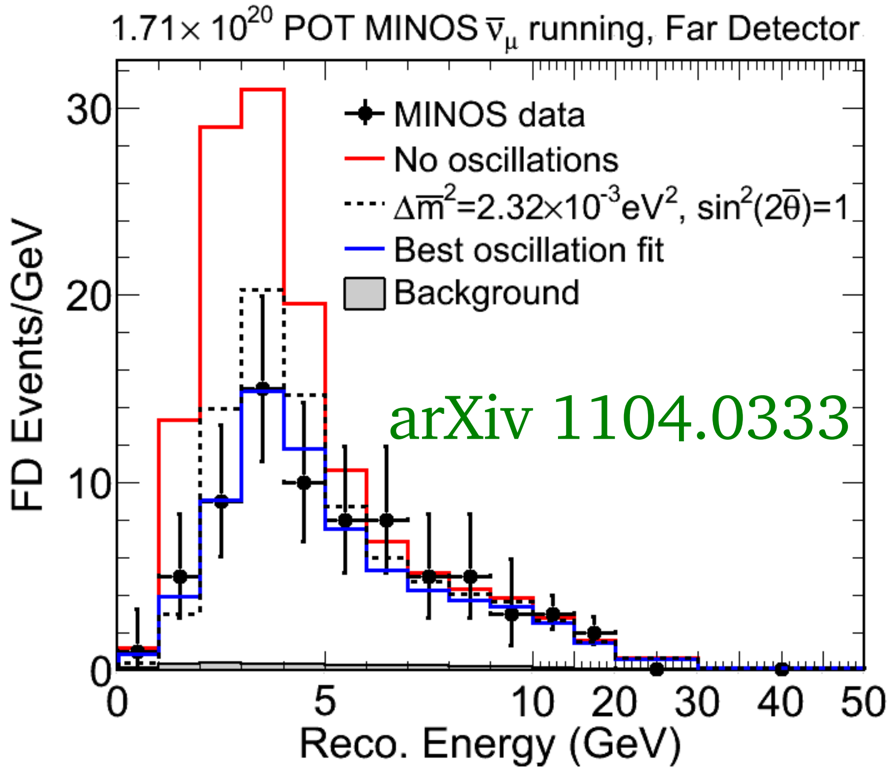
Anti-ν_μ disappearance

arXiv 1104.0333

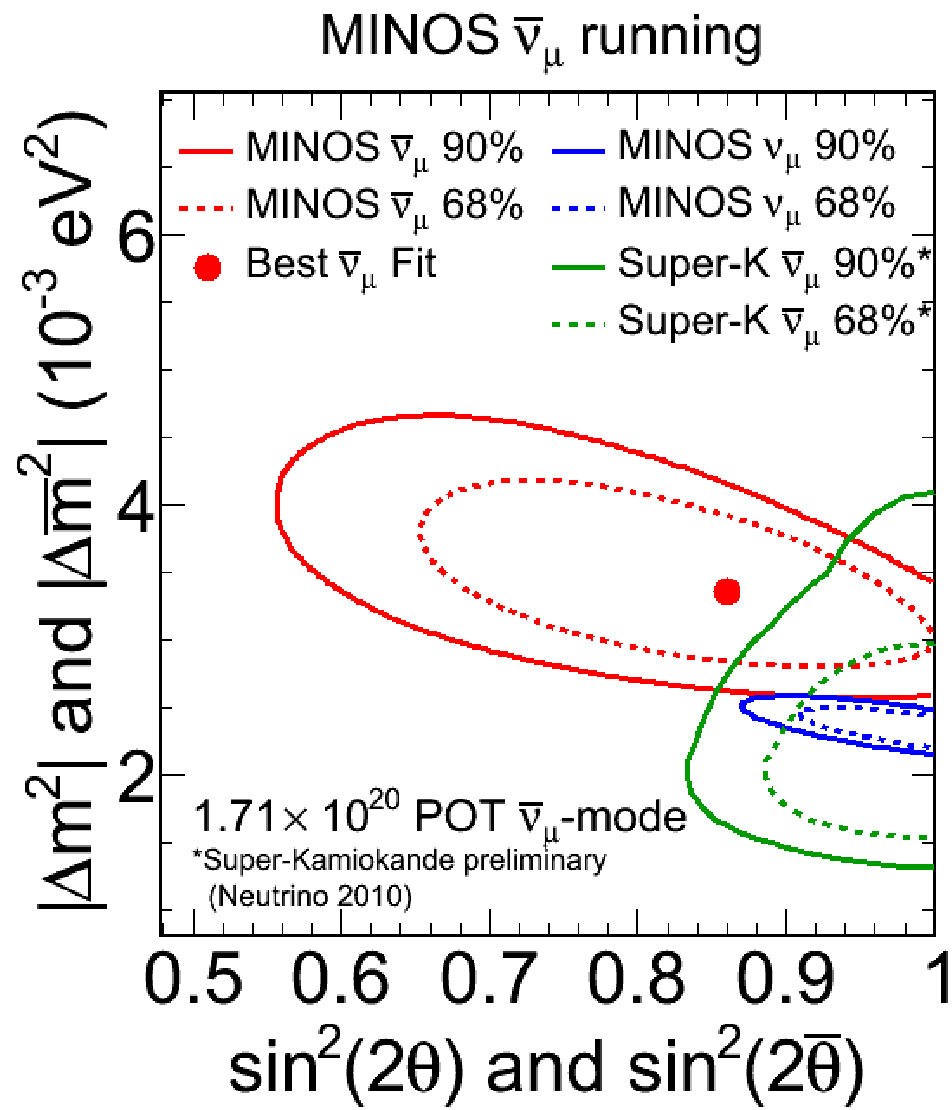
Using a $\bar{\nu}_\mu$-optimized beam

- Reconstruction measures charge/momentum for all tracks
- Well modeled and checked in the ND by moving vertex region, changing track containment and quality requirements, reversing the magnetic field.
- At the far detector, accounting for oscillations, the wrong sign impurity is $<3\%$ in both the ν_μ and anti-$\bar{\nu}_\mu$ beams

Anti-ν_μ disappearance



arXiv 1104.0333

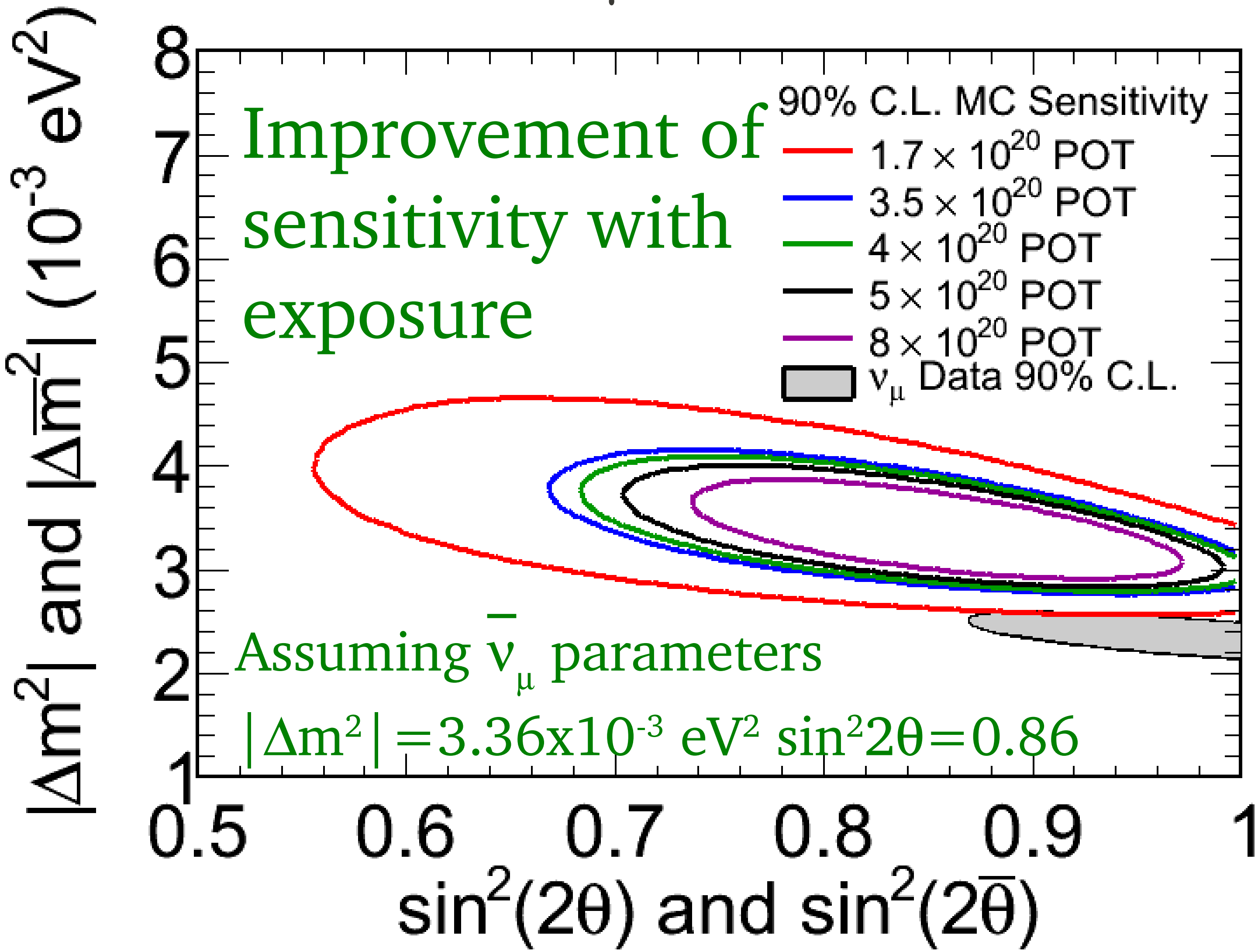


Best Fit Parameters (68% CL)

$$|\Delta\overline{m}^2| = 3.36\ ^{+0.46}_{-0.40}\,\text{(stat)} \pm 0.06\,\text{(sys)} \times 10^{-3}\ \text{eV}^2$$

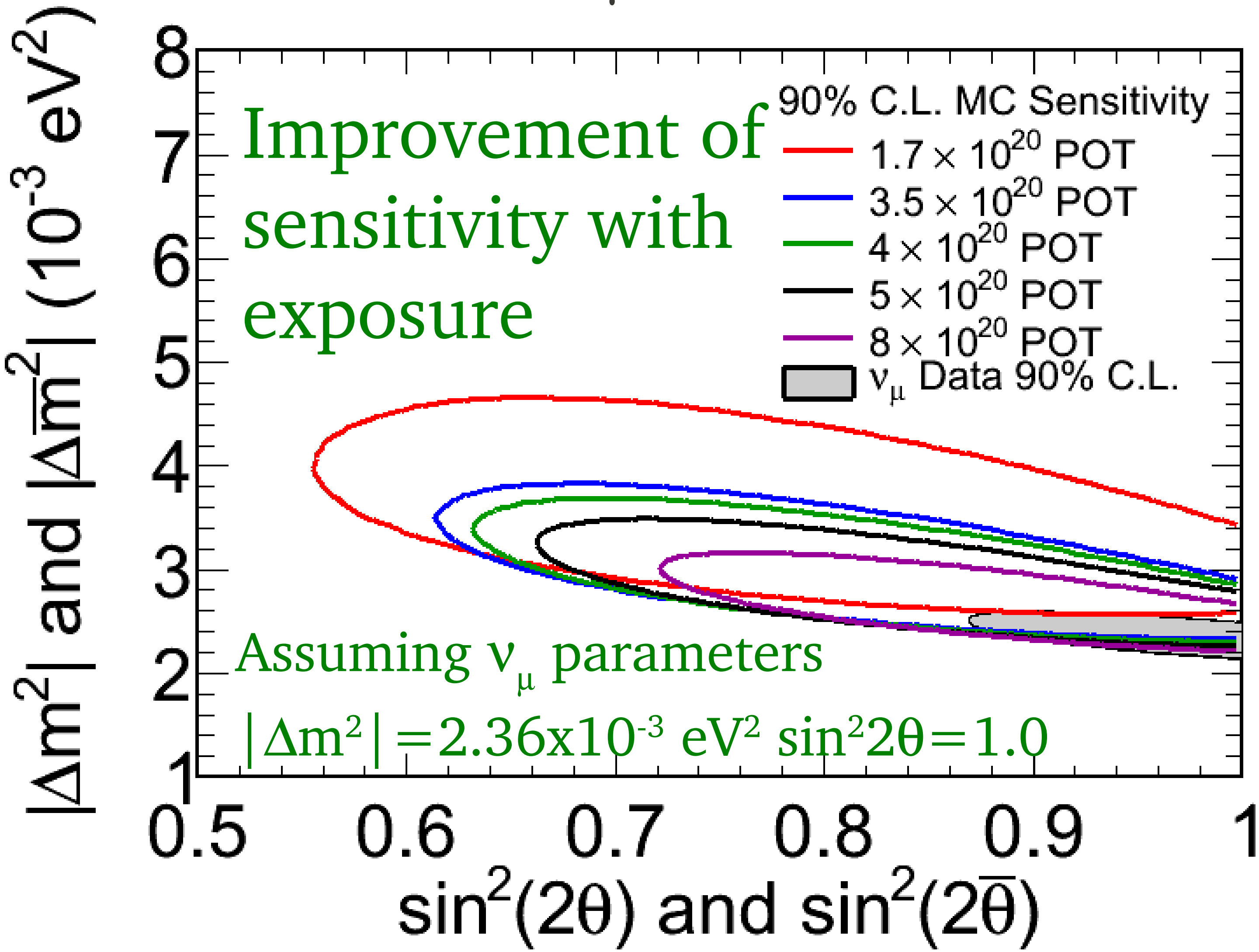
$$\sin^2 2\overline{\theta} = 0.86 \pm 0.11\,\text{(stat)} \pm 0.01\,\text{(sys)}$$

Anti-ν_μ Future



MINOS has requested a total of $4.0\text{x}10^{20}$ POT of anti-neutrino optimized beam → $3.0\text{x}10^{20}$ POT in hand

Anti-ν_μ Future

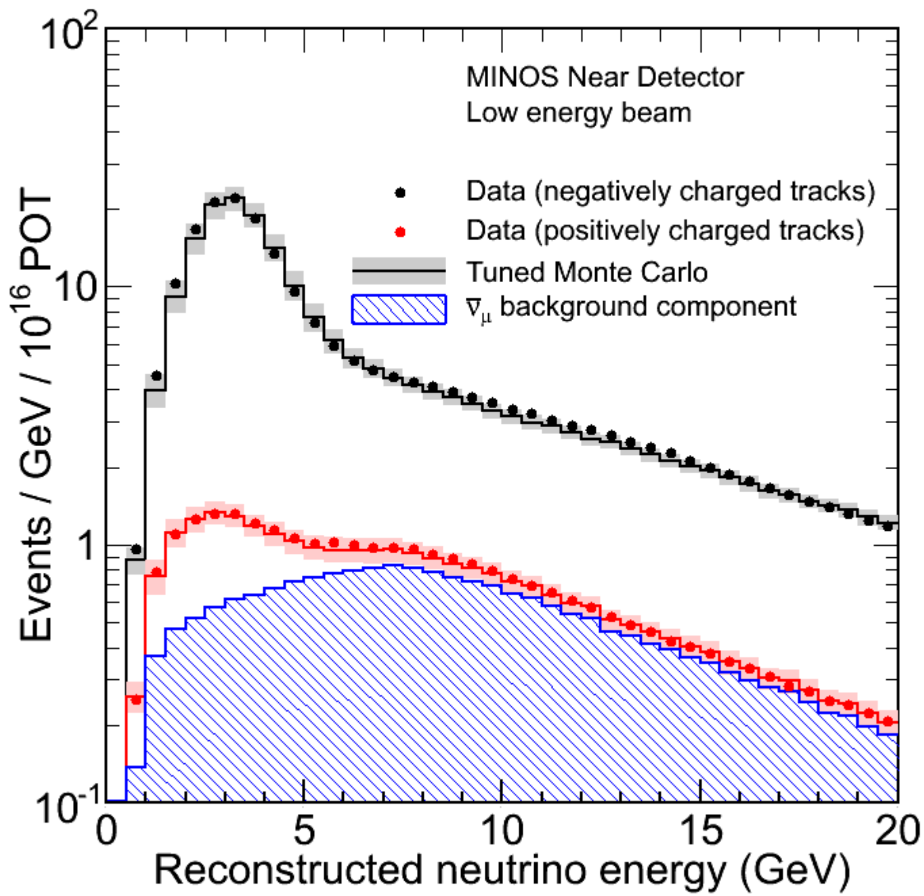


MINOS has requested a total of 4.0×10^{20} POT of anti-neutrino optimized beam → 3.0×10^{20} POT in hand

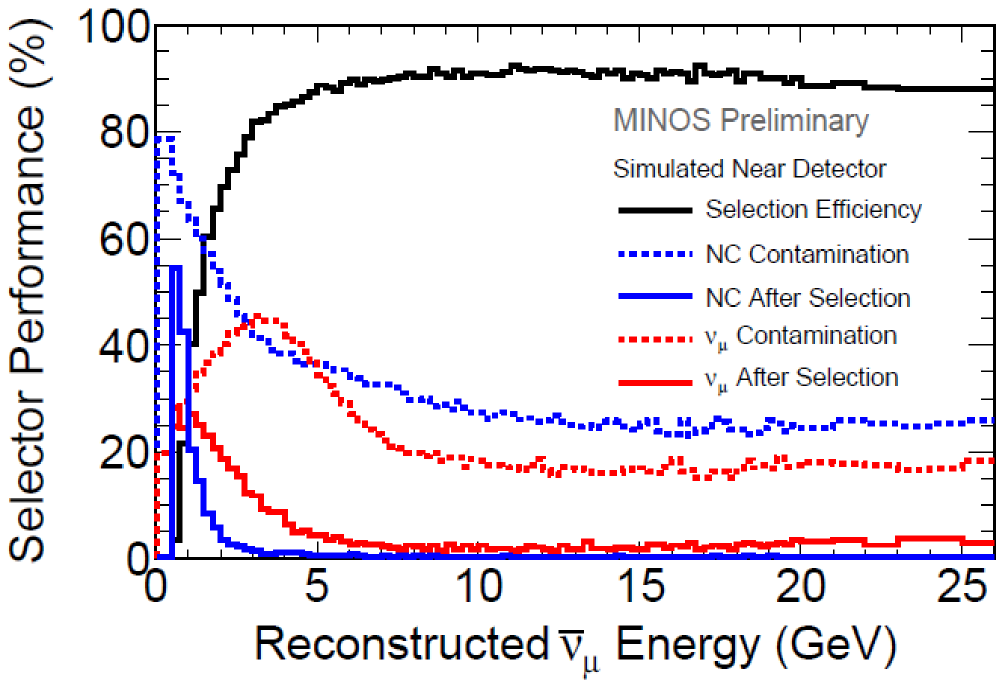
New MINOS Result

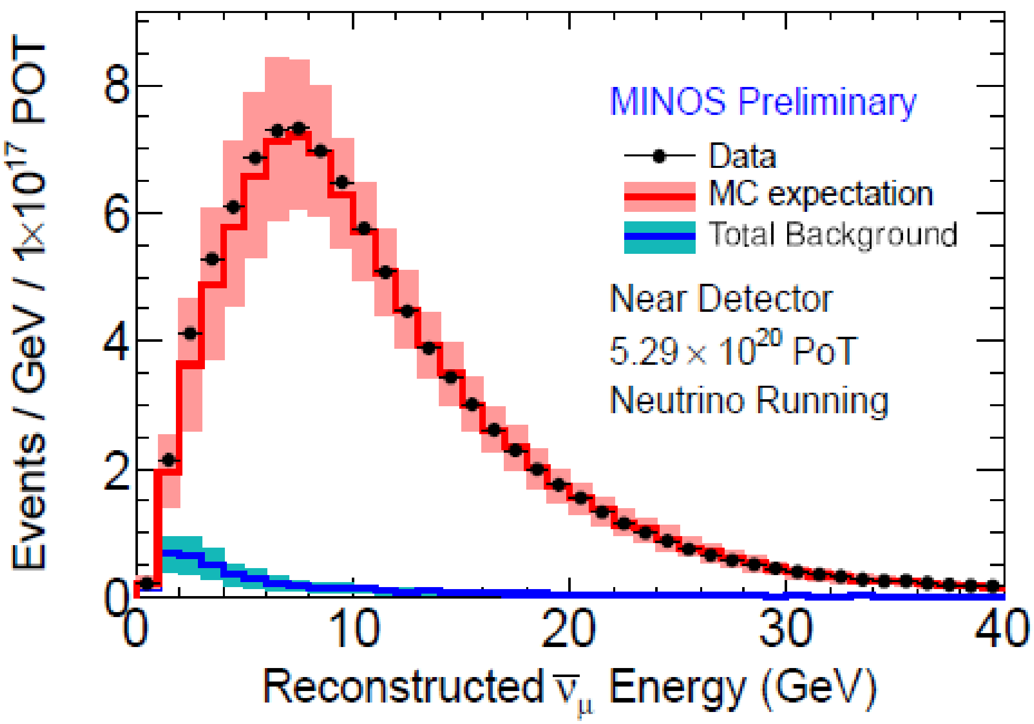
Anti-ν_μ disappearance in the ν_μ beam

- $\bar{\nu}_\mu$ are about 7% of the ν_μ–optimized beam
- High energy, but still affected by oscillations
- may be sensitive to exotic phenomena, such as $\nu_\mu \rightarrow \bar{\nu}_\mu$ transitions



- Useful check on ν_μ vs $\bar{\nu}_\mu$ identification

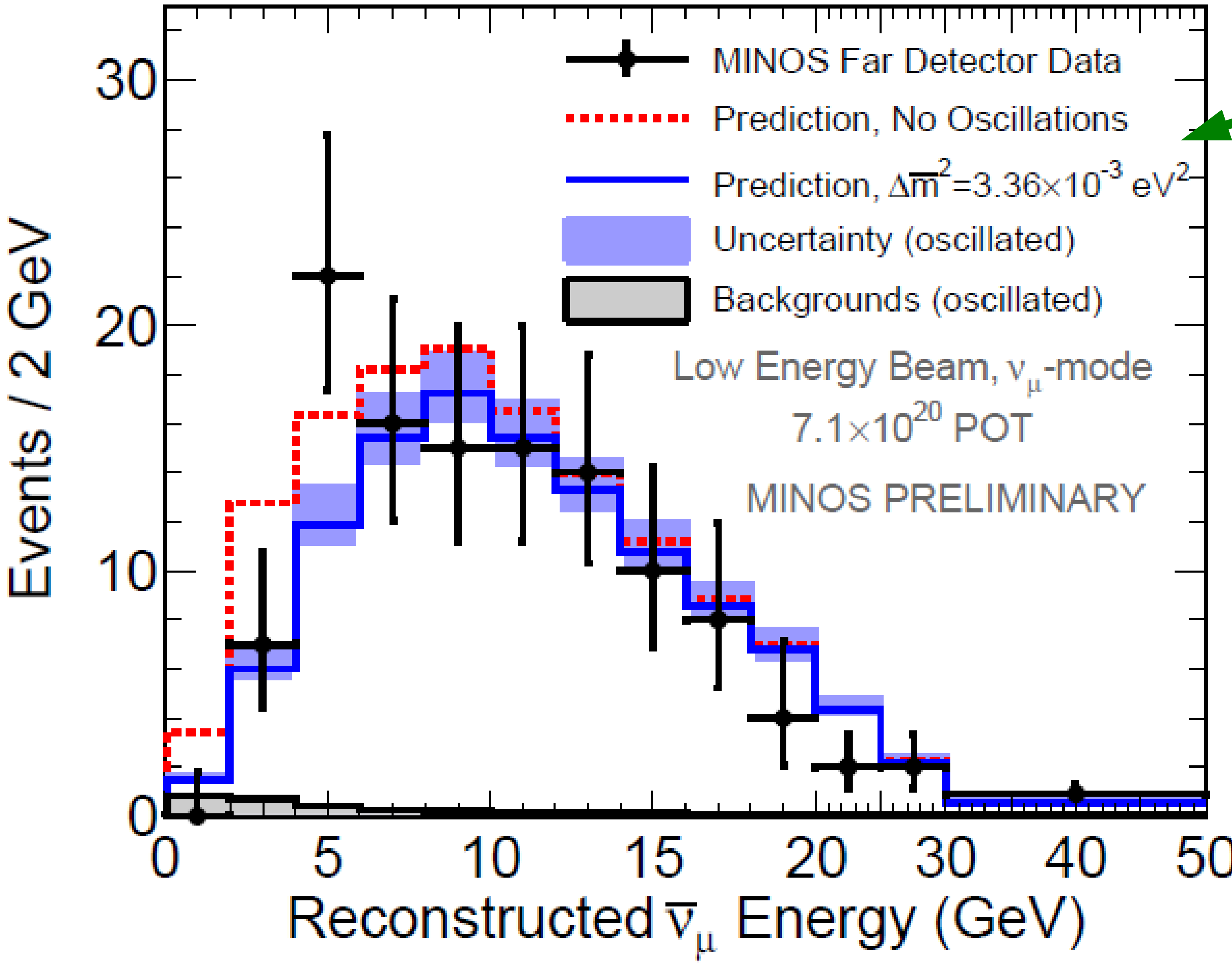




Anti-ν_μ selection

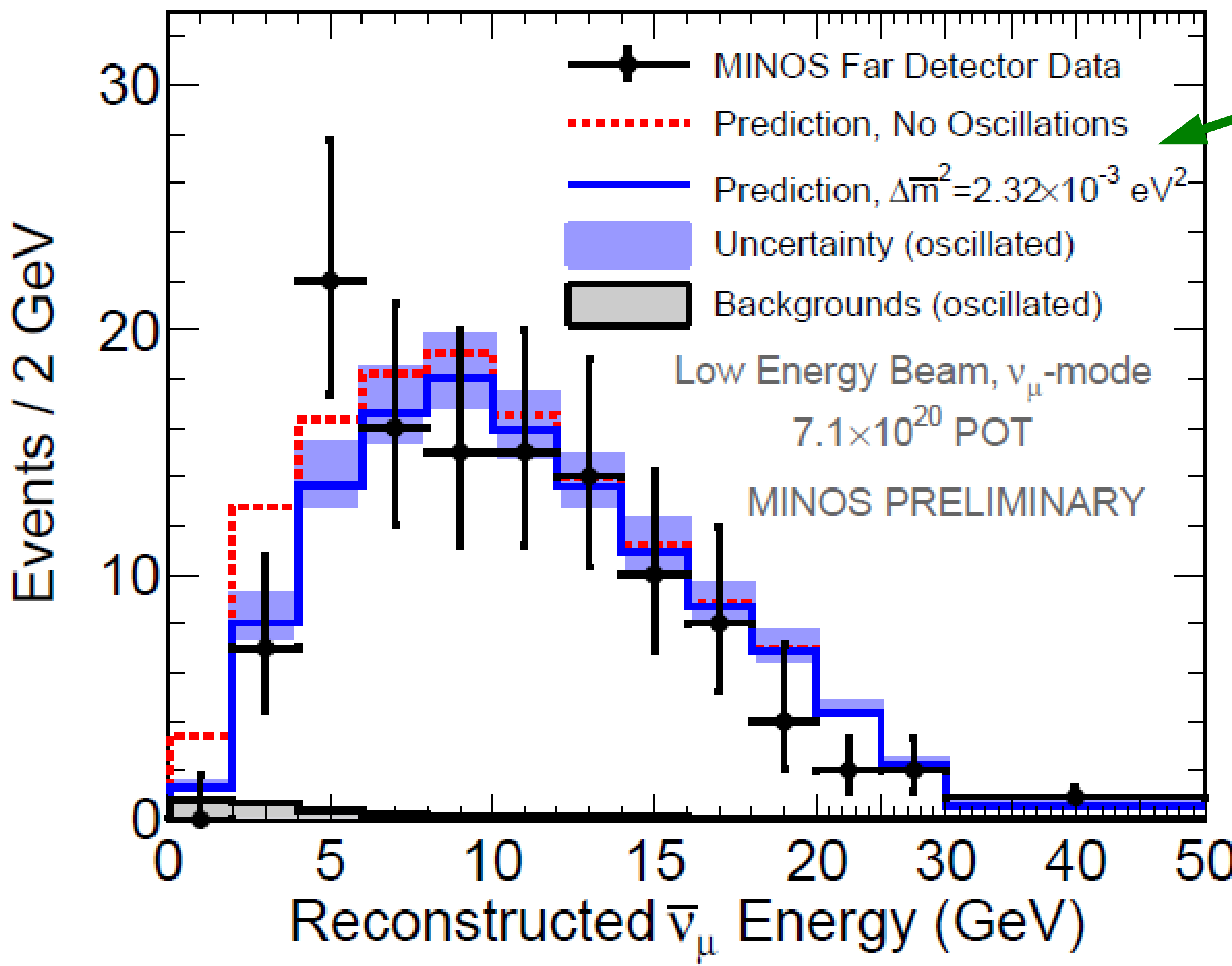
- Simple selection of events with a positively charged track has large backgrounds from NC and highly inelastic ν_μ-CC
- These backgrounds are suppressed by using
  - A multi-variable CC/NC discriminator which uses the event topology
  - The uncertainty on q/p reported by the track fitter.
  - A direction of curvature variable called “relative angle” which uses the track topology, independent of the track fitter
- The selection efficiency is 90% and the purity of the $\bar{\nu}_\mu$ sample is 95%

Anti-ν_μ disappearance in the ν_μ beam



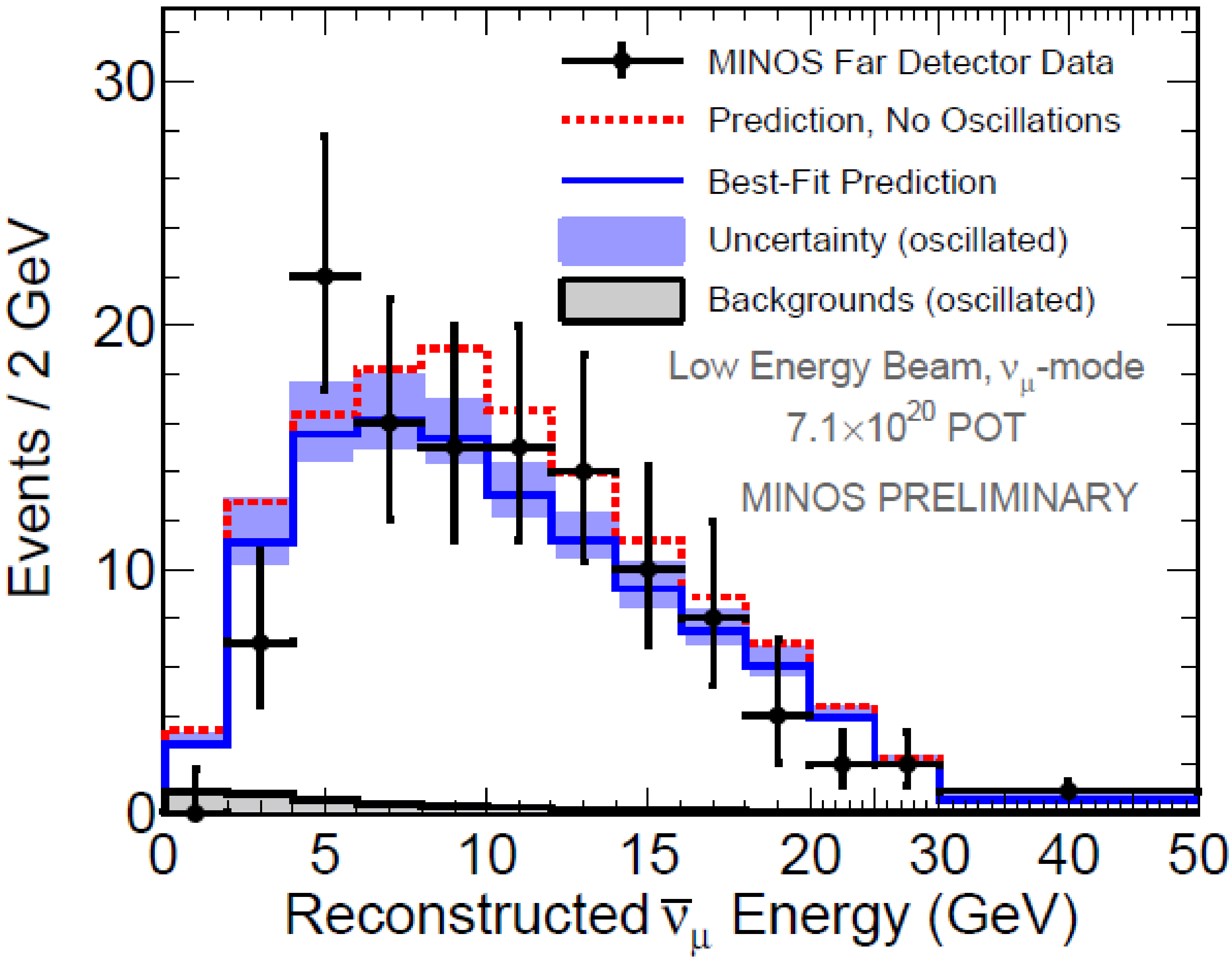
Prediction from measuring $\bar{\nu}_\mu$ in a $\bar{\nu}_\mu$ optimized beam

Anti-ν_μ disappearance in the ν_μ beam



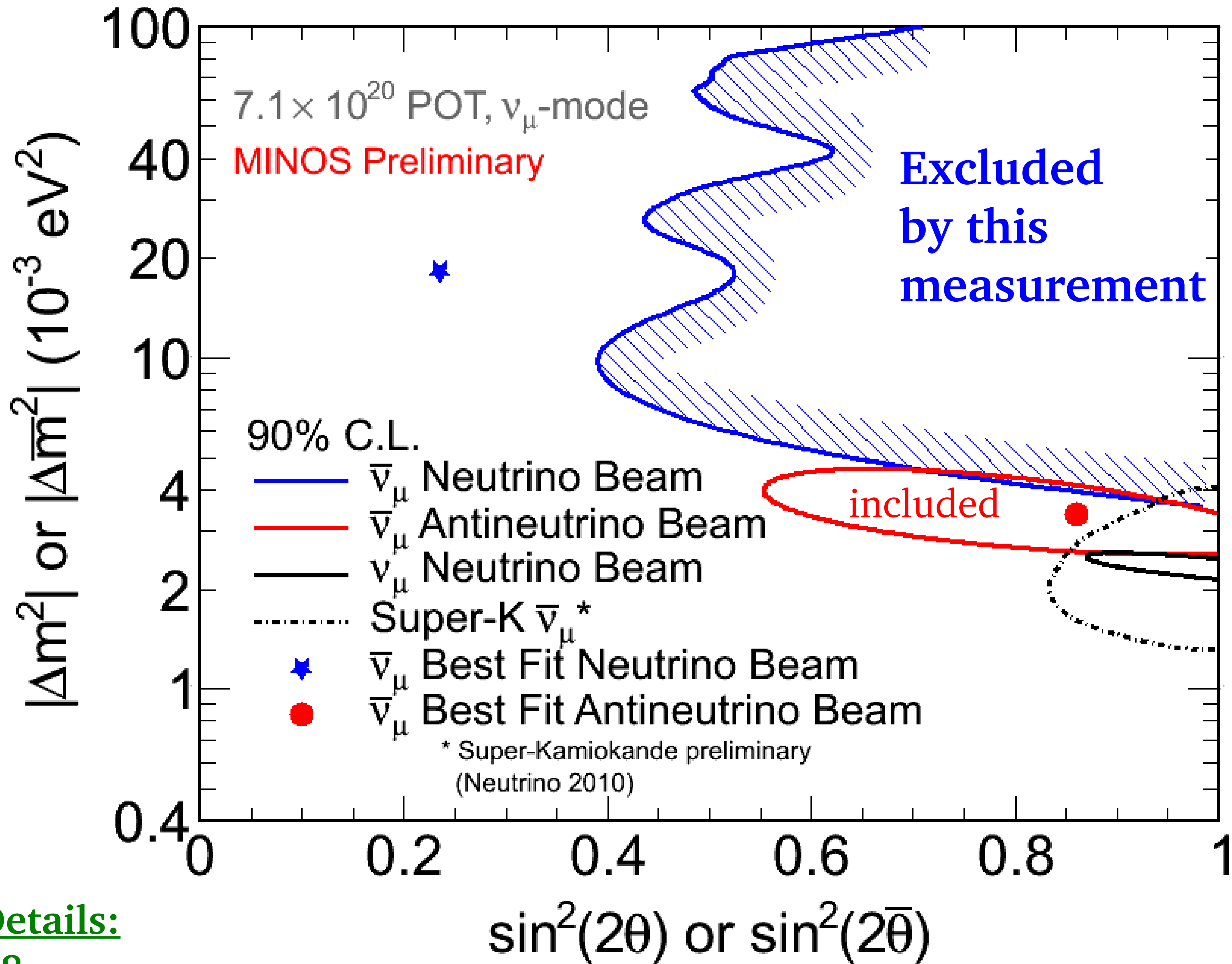
Prediction from measuring ν_μ in a ν_μ optimized beam

Anti-ν_μ disappearance in the ν_μ beam



Best fit from this analysis

Anti-ν_μ disappearance in the ν_μ beam



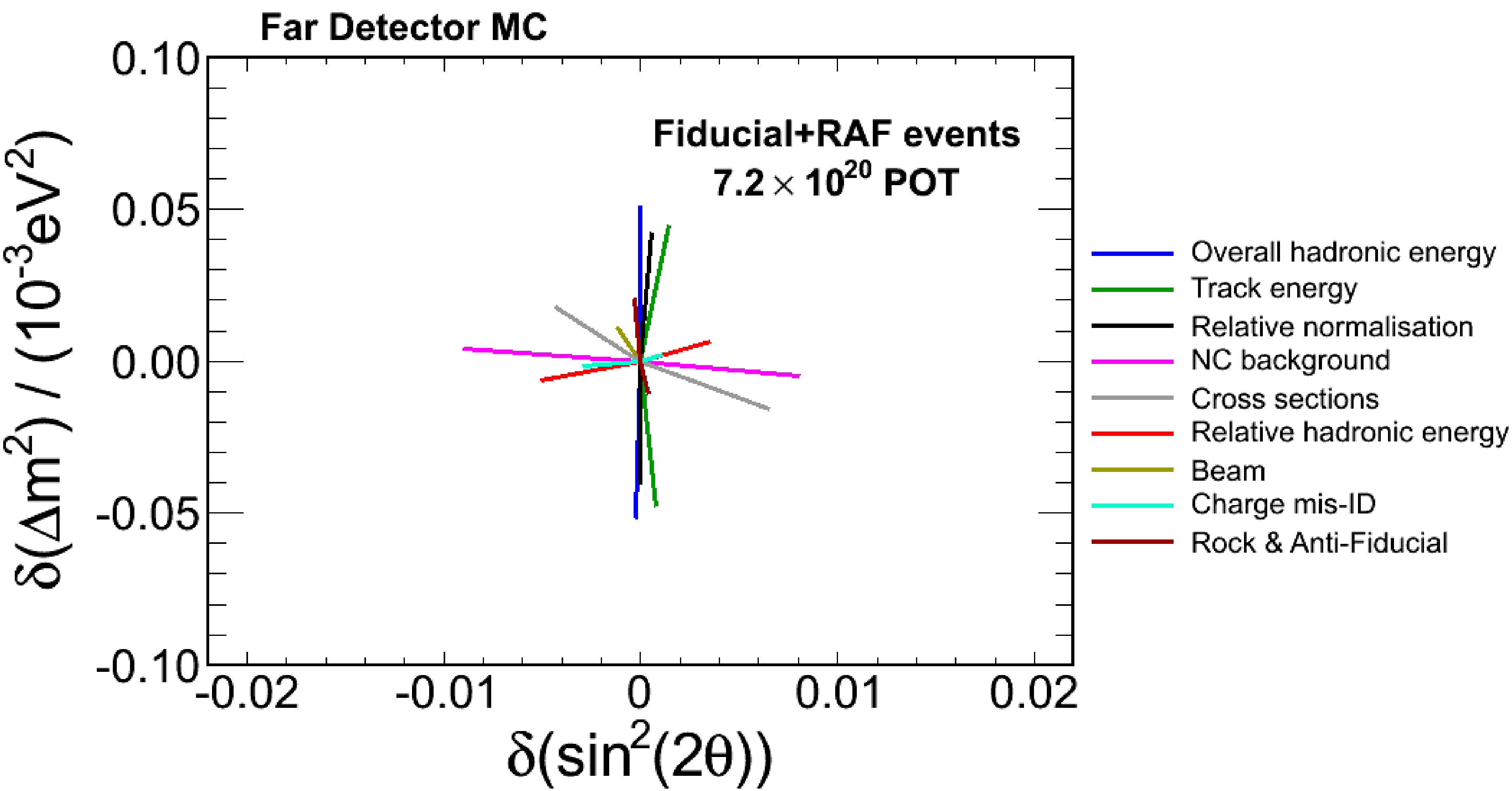
Additional Details:
B. Pahlka - J8
R. Sharma - J8

Conclusions

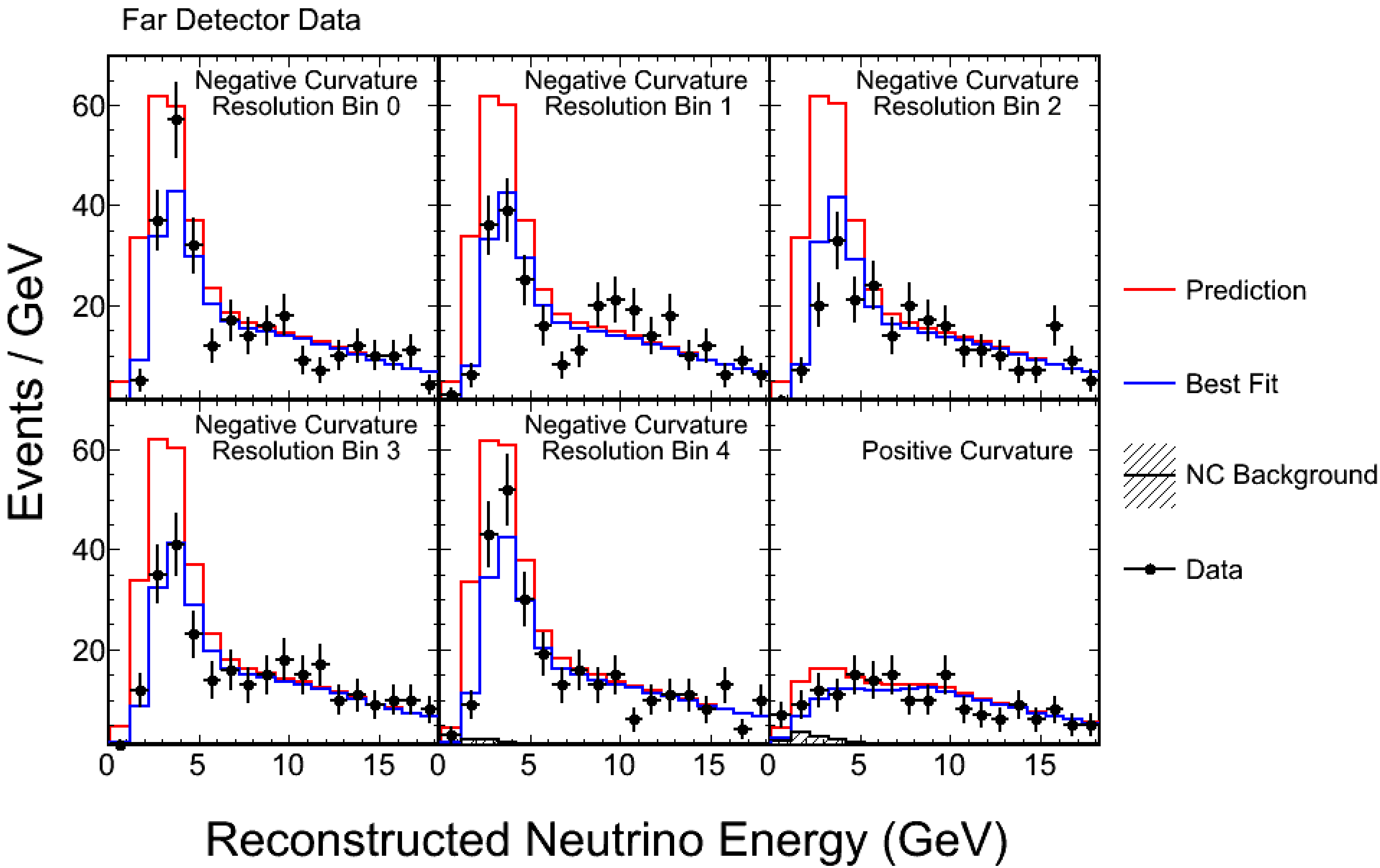
- Neutrinos are the most poorly understood of the known SM particles. They've surprised us in the past and may do so in the future.
- Accelerator based oscillation experiments address important questions:
  - What is the value of θ_{13}? Is there CP violation ($\delta \neq 0,\pi$)?
  - Which mass hierarchy? e.g., $m_3 > m_1$ or $m_3 < m_1$?
  - Maximal mixing: $\sin^2 2\theta_{23} = 1$? Symmetry principal?
  - Is the PMNS matrix really unitary? Are oscillations the right idea?
  - How do we explain MiniBooNE & LSND?
  - Do neutrinos experience non-standard interactions?
- International program with experiments that are
  - running, (MINOS,OPERA,T2K, MiniBooNE)
  - being built (NOvA, MicroBoone)
  - and in the design stage (LBNE, T2KK, INO, LAGUNA, ν-factory, etc.)
- I think we are in for an exciting future.

Backup Slides

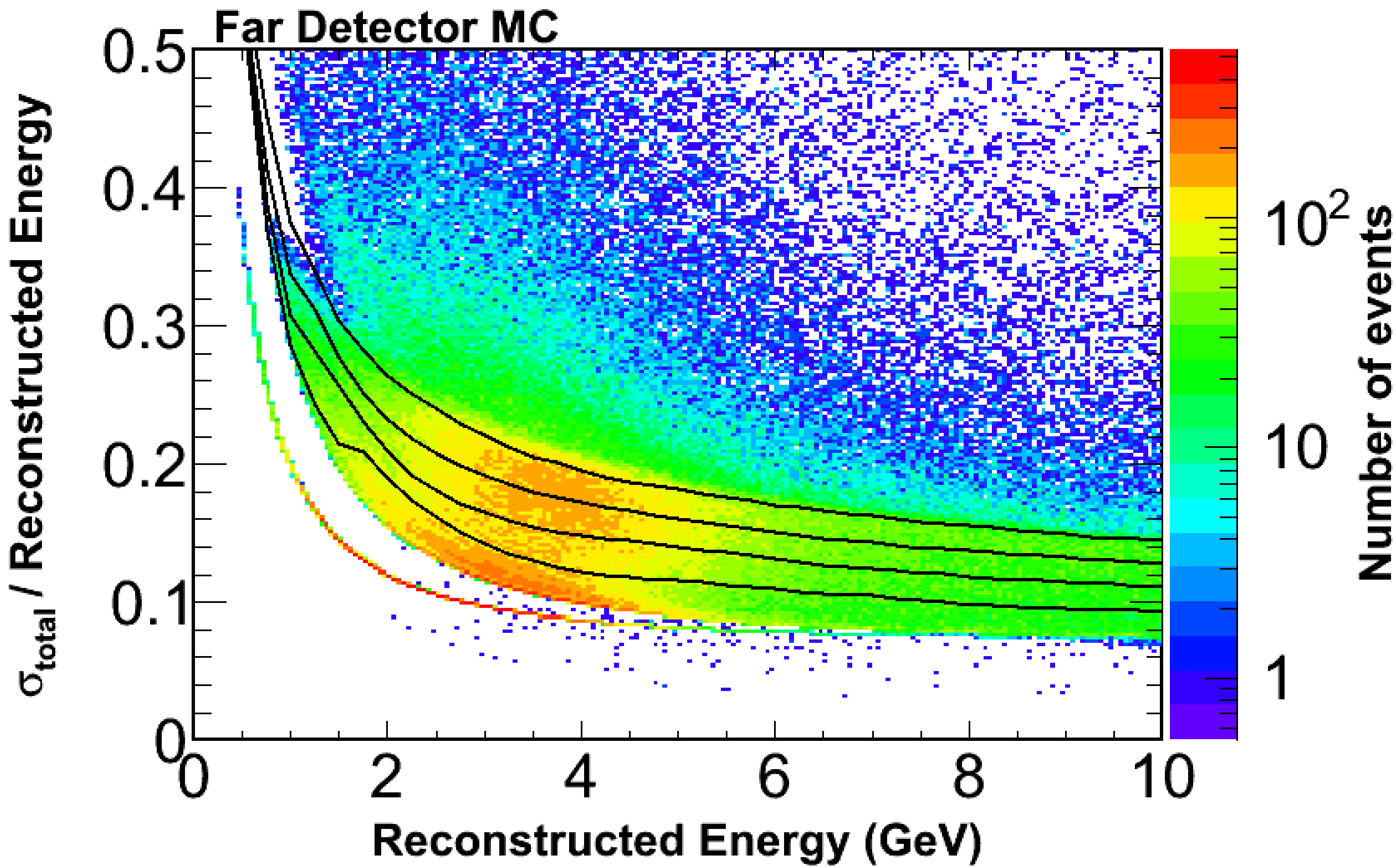
Systematics for 2010 CC



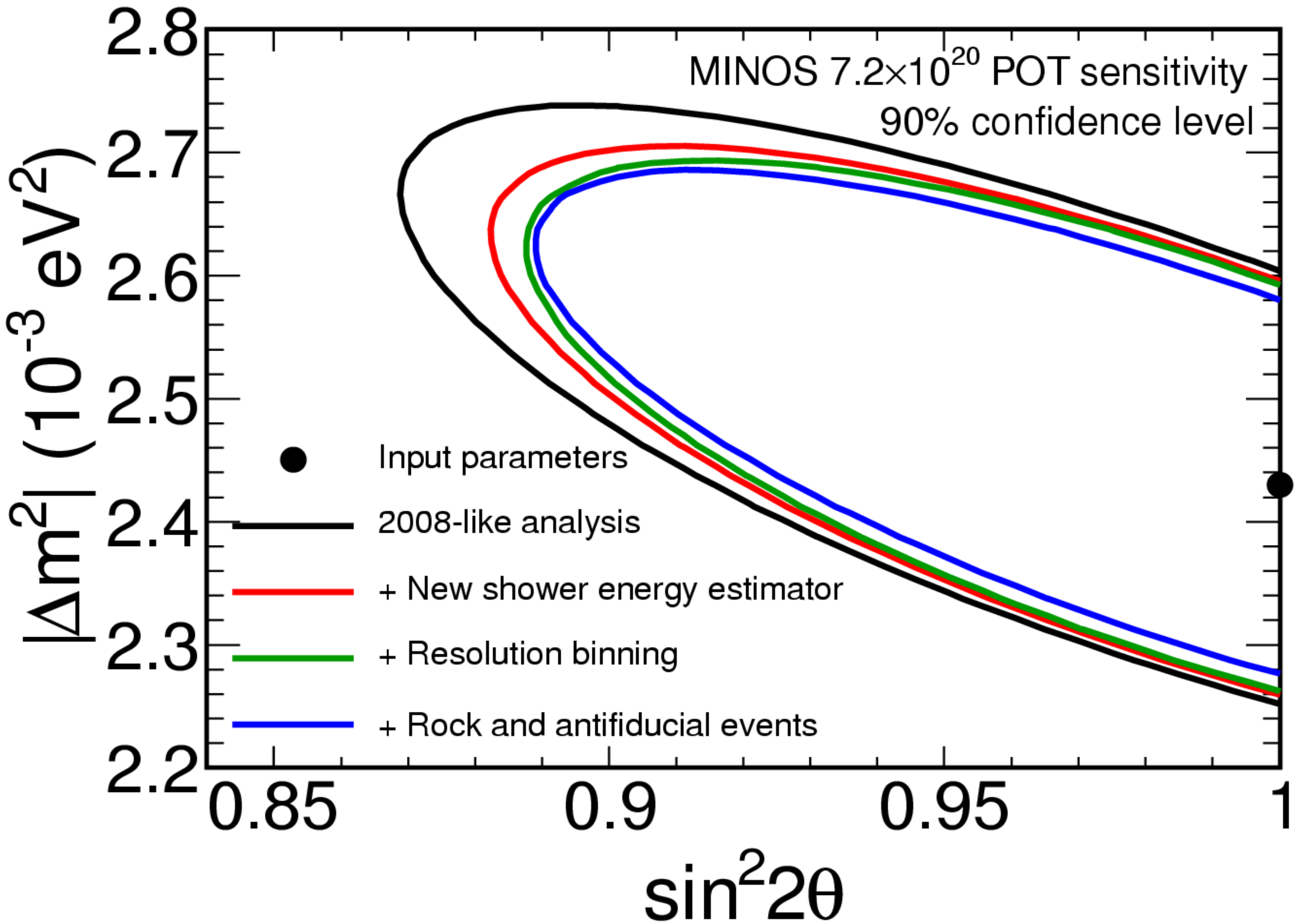
Resolution Bins 2010 CC



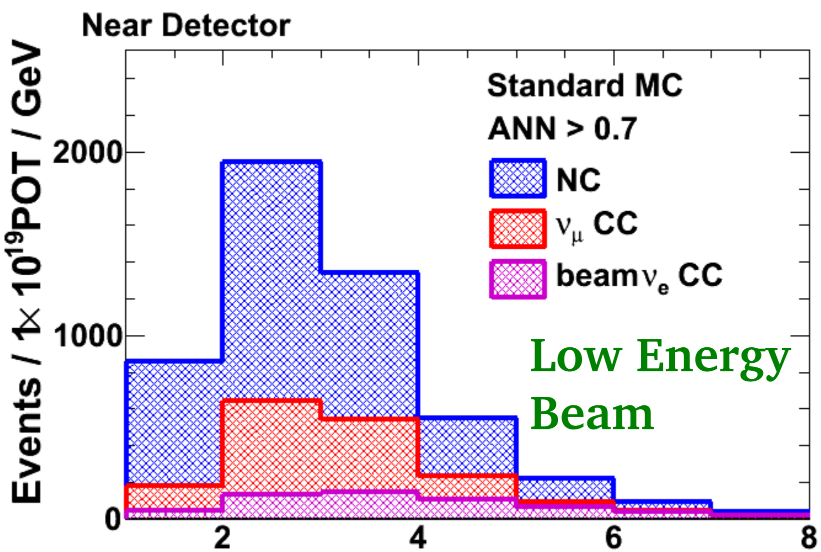
Resolution Binning 2010 CC

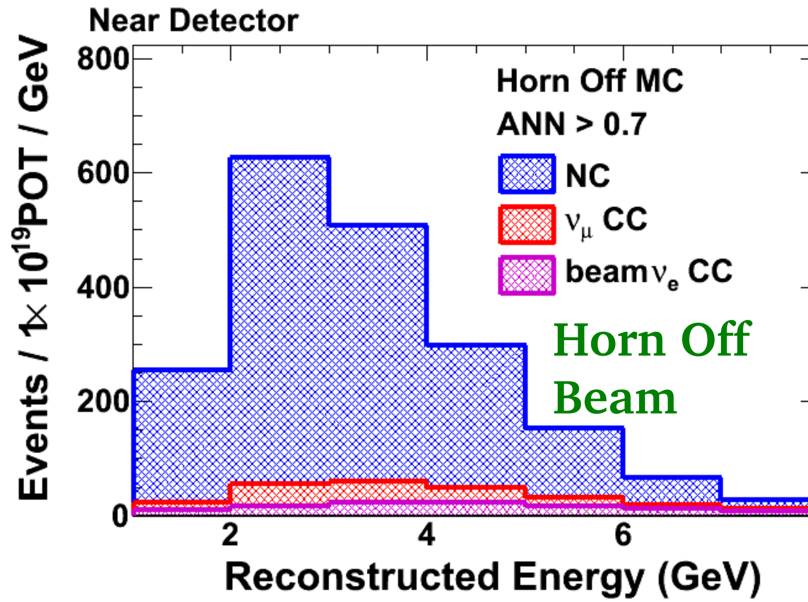


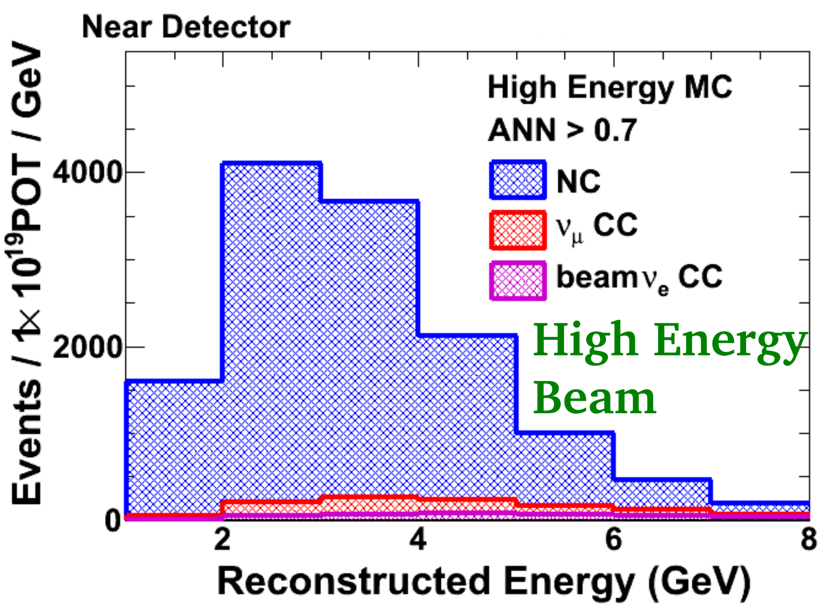
Analysis Improvements 2010 CC



Decompostion for ν_e



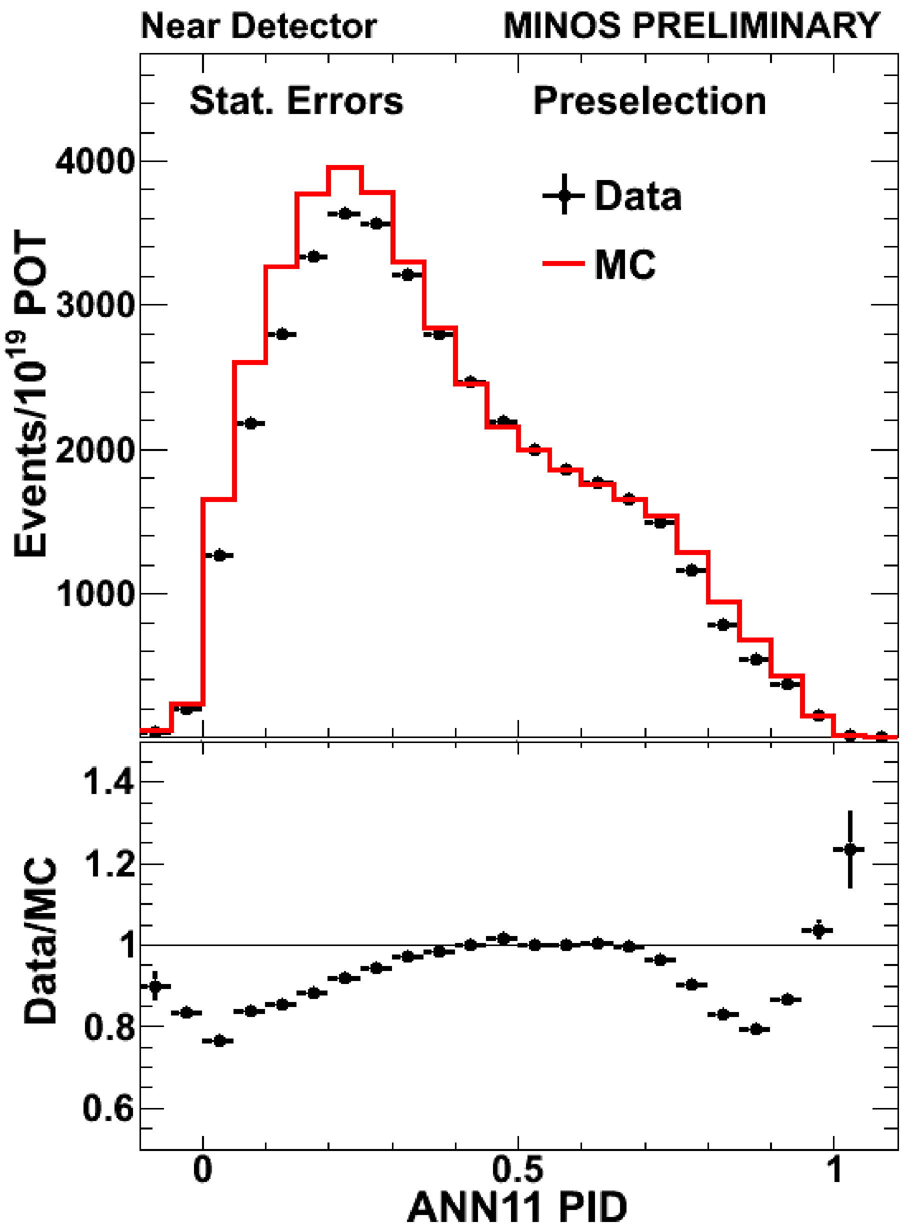


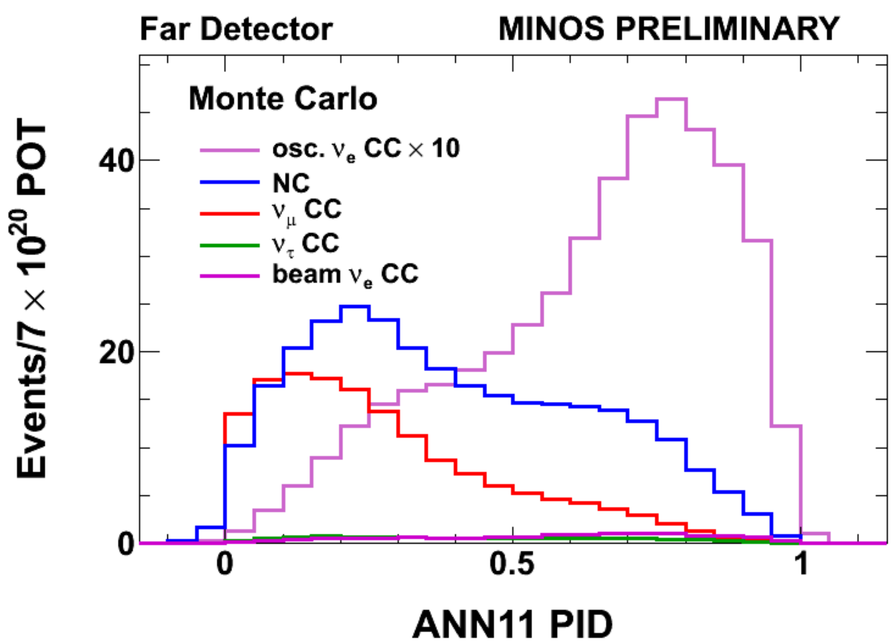


- changing beam configurations modifies CC/NC/ν_e composition in each bin
- Relative compositions constrained by tuning beam simulation to ν_μ-CC in multiple beam configurations
- Permits you replace terms and to solve for composition in Low Energy beam

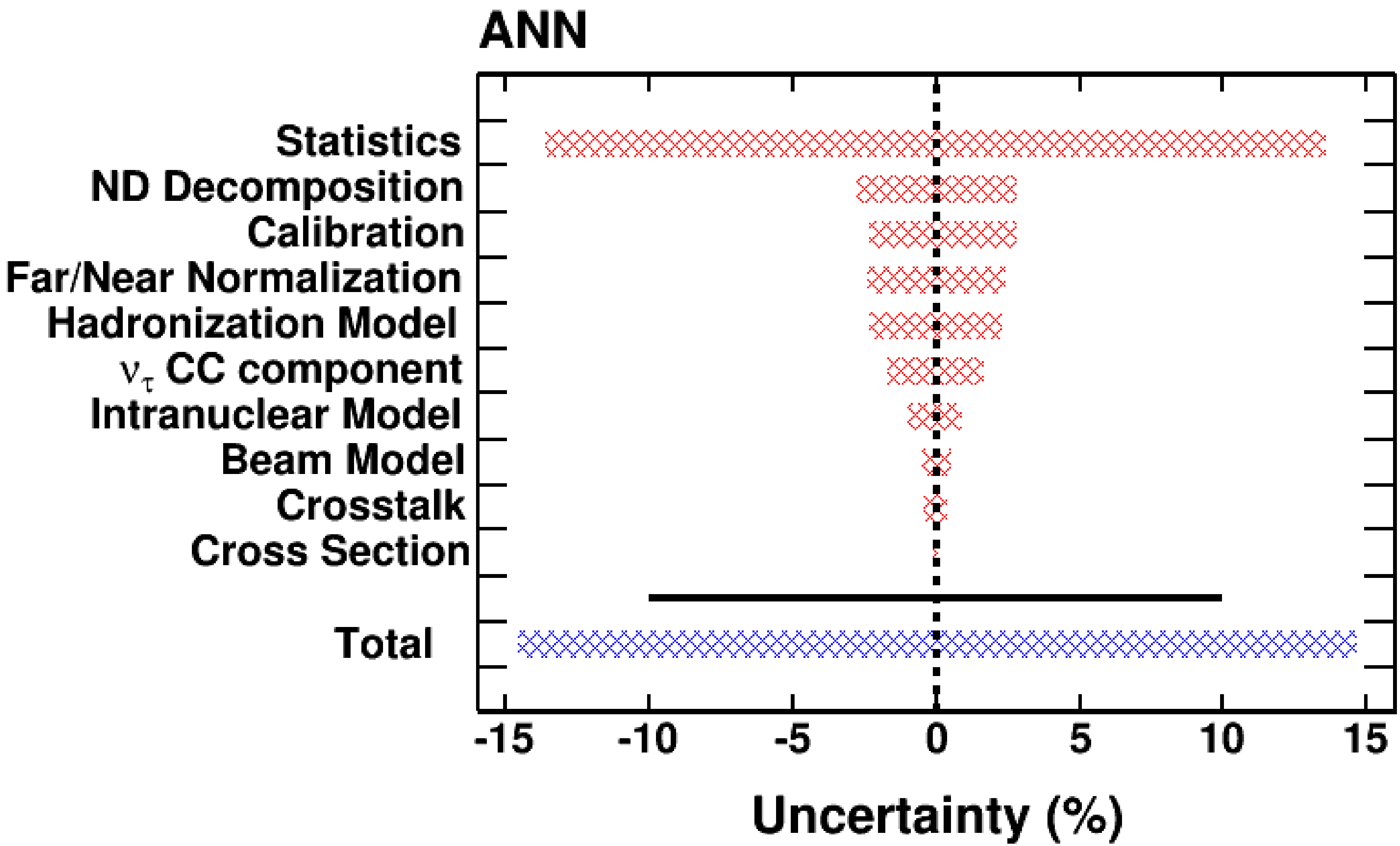
$$x_{HighE}^{NC} = x_{LowE}^{NC} \frac{x_{HighE,\,MC}^{NC}}{x_{LowE,\,MC}^{NC}}$$

ν_e PID


Near Detector
MINOS PRELIMINARY
Stat. Errors
Preselection
Data
MC
Events/10^{19} POT
4000
3000
2000
1000
Data/MC
1.4
1.2
1
0.8
0.6
0
0.5
1
ANN11 PID


Far Detector
MINOS PRELIMINARY
Monte Carlo
osc. ν_e CC $\times$ 10
NC
ν_μ CC
ν_τ CC
beam ν_e CC
Events/7 $\times$ 10^{20} POT
40
20
0
0
0.5
1
ANN11 PID

Uncertainties – ν_e



T2K ν_e selection

T2K-SK events	Data	MC	
		No oscillation	Oscillation $\Delta m^2 = 2.4 \times 10^{-3}$ (eV²) $\sin^2 2\theta_{23} = 1.0$ $\theta_{13}=0$
Fully-Contained	33	54.5	24.6
Fiducial Volume, $E_{vis} > 30$MeV	23	36.8	16.7
Single-ring e-like (P_e>100MeV/c)	2	1.5 ±0.7	1.3 ±0.6

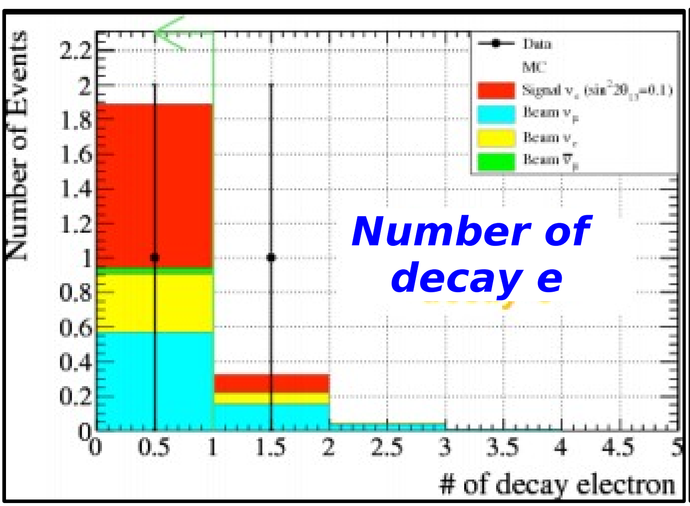
Additional background rejection:

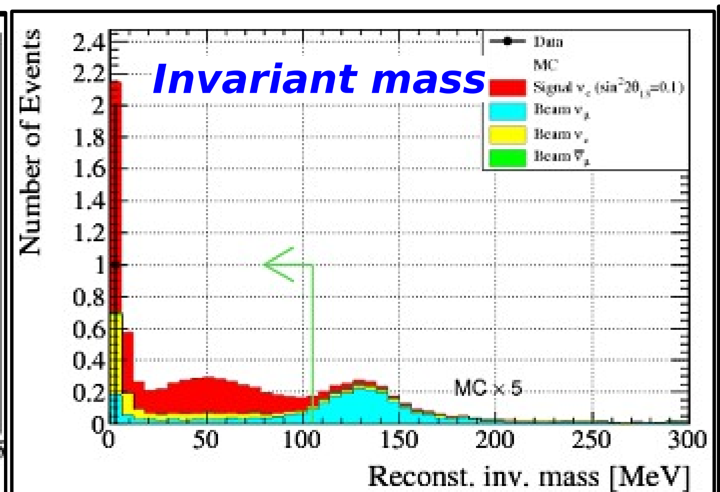
- no decay electron
- $m_{\gamma\gamma}$ < 105 MeV assuming second ring exist
- reconstructed Ev < 1250 MeV

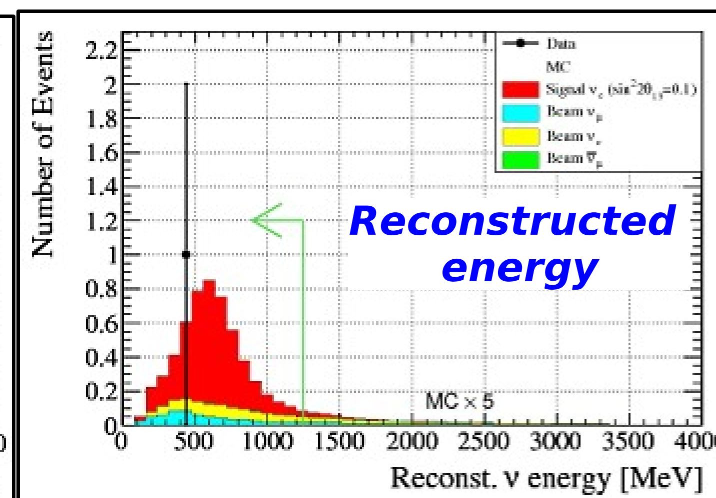
65.9% efficiency for signal

One candidate ν_e event remains!

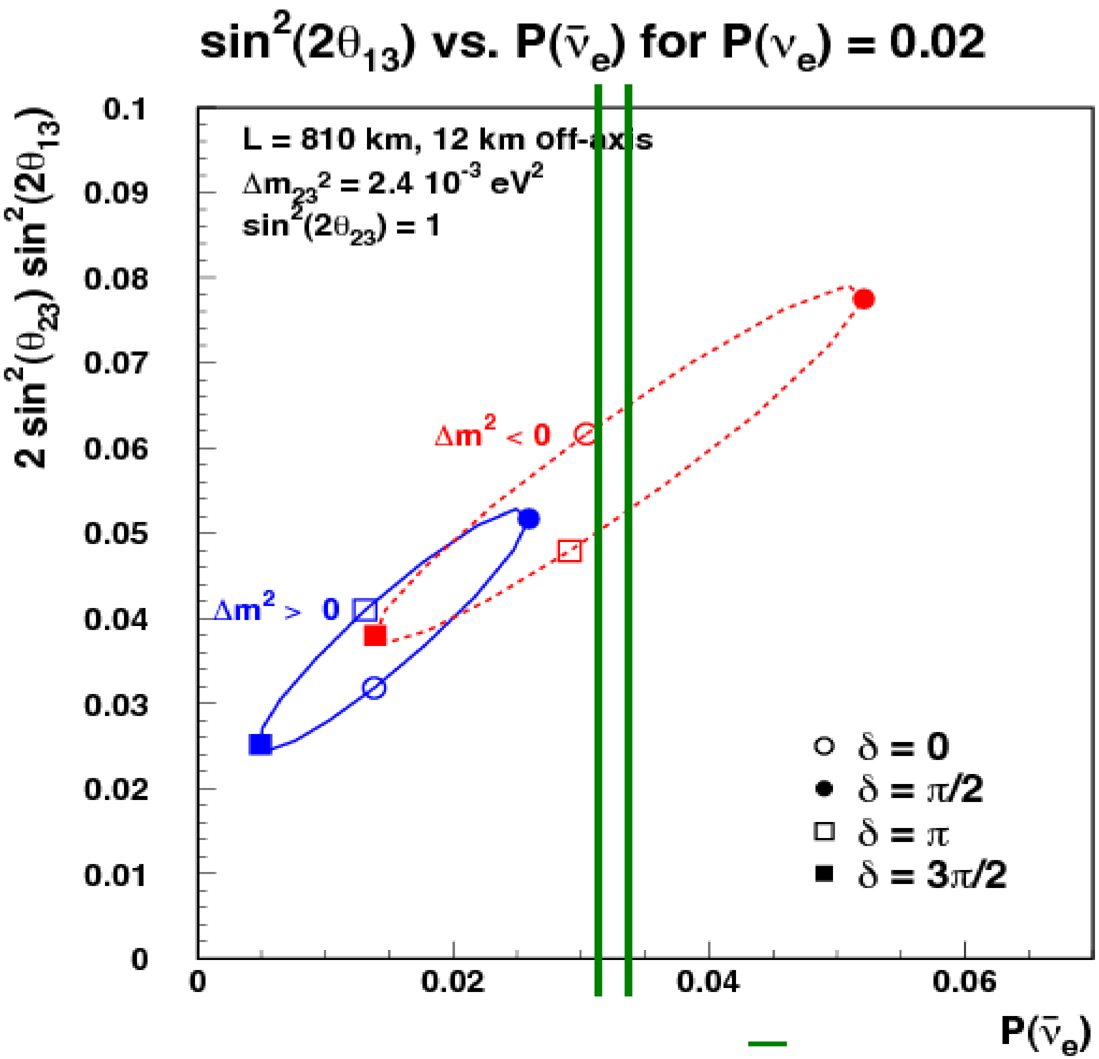
T2K preliminary







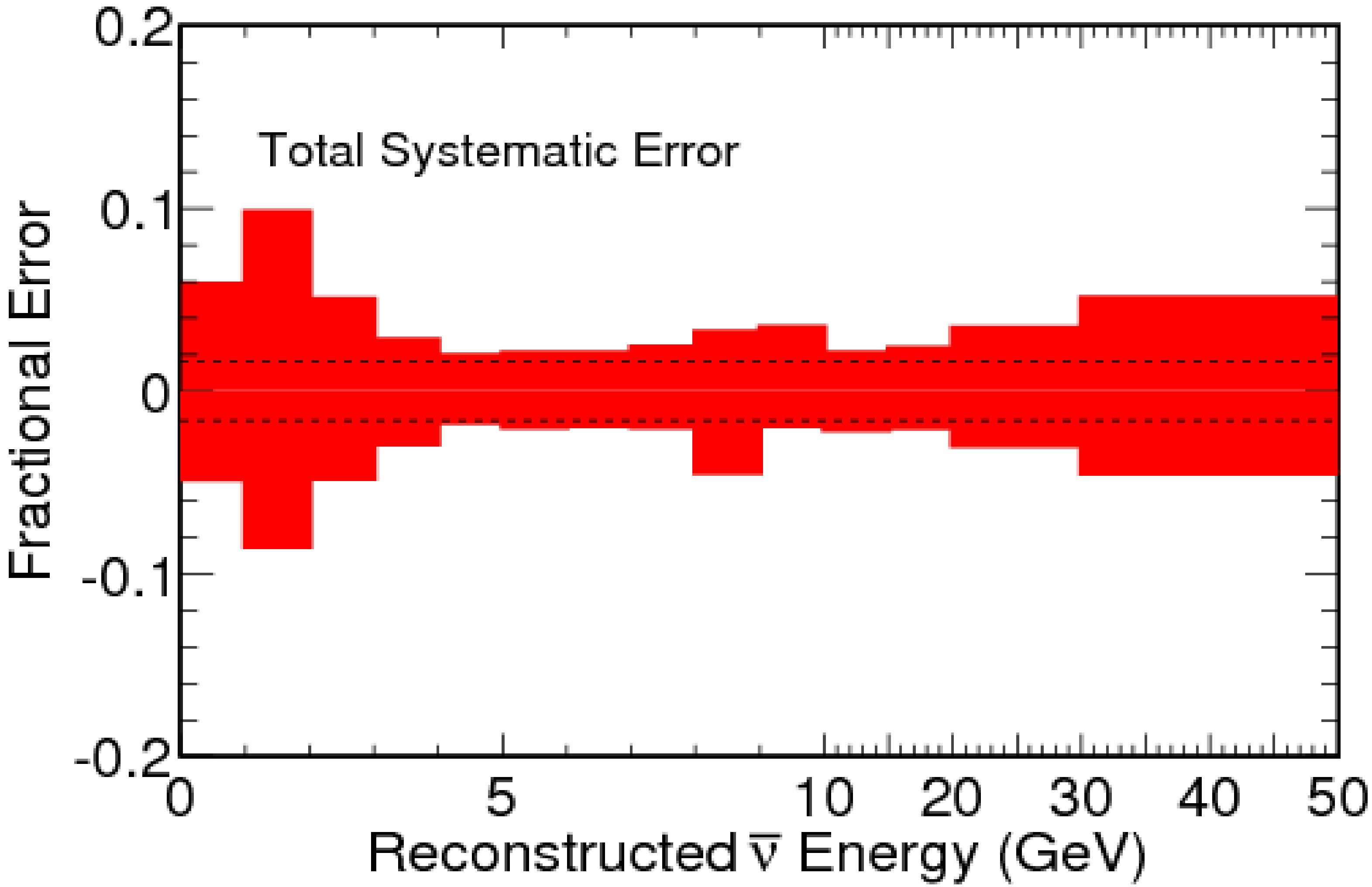
Mass Hierarchy from NOvA



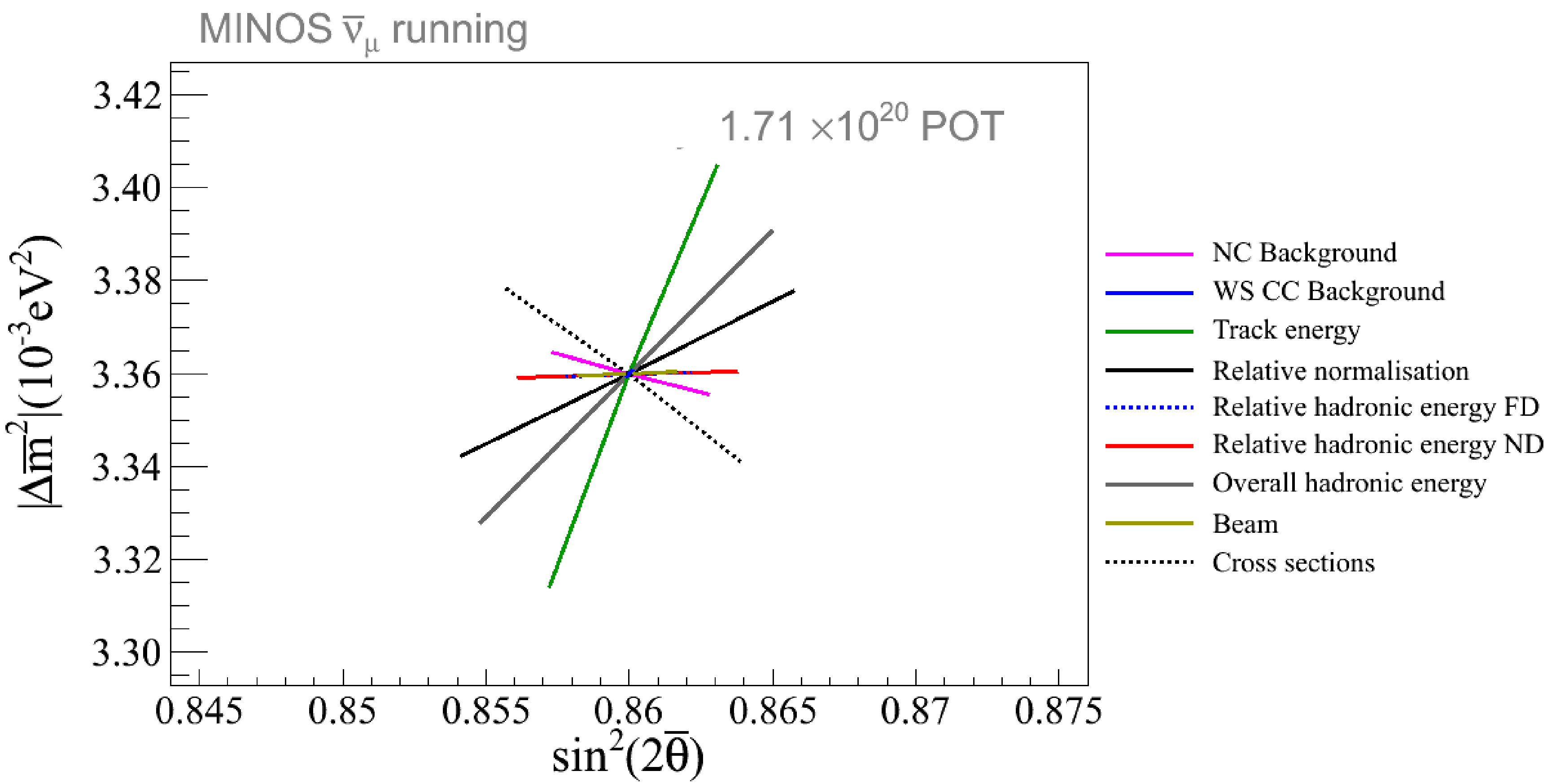
Measured $P(\bar{\nu}e)$

- Assume you measure $P(\nu_e)=0.02$
- That measurement could arise from any of the places along the ellipses
- Then measure $P(\bar{\nu}_e)$, which picks out a vertical slice.
- You determine the mass hierarchy for slices which intersect only one color.

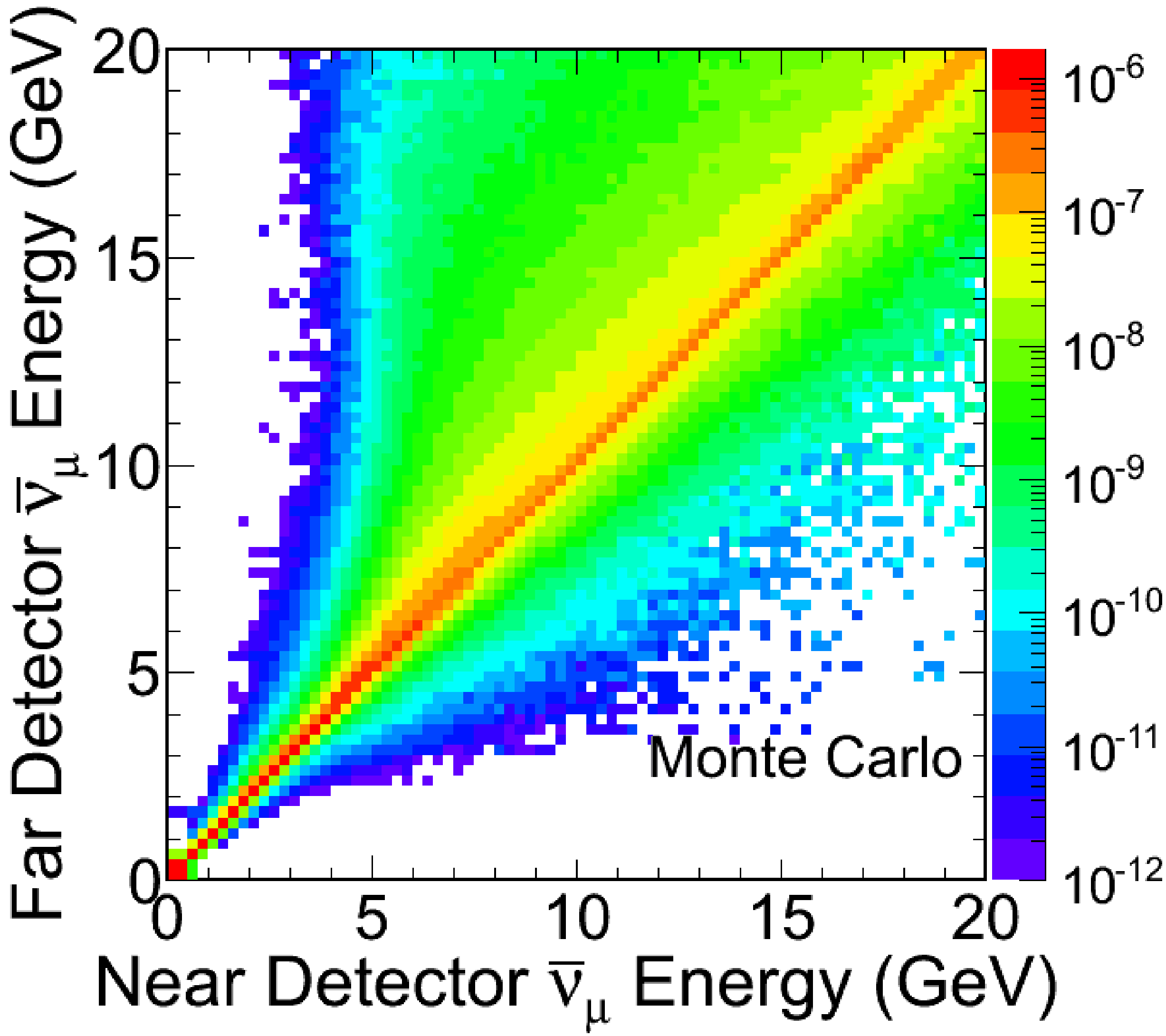
Systematic Errors – $\bar{\nu}_\mu$ RHC



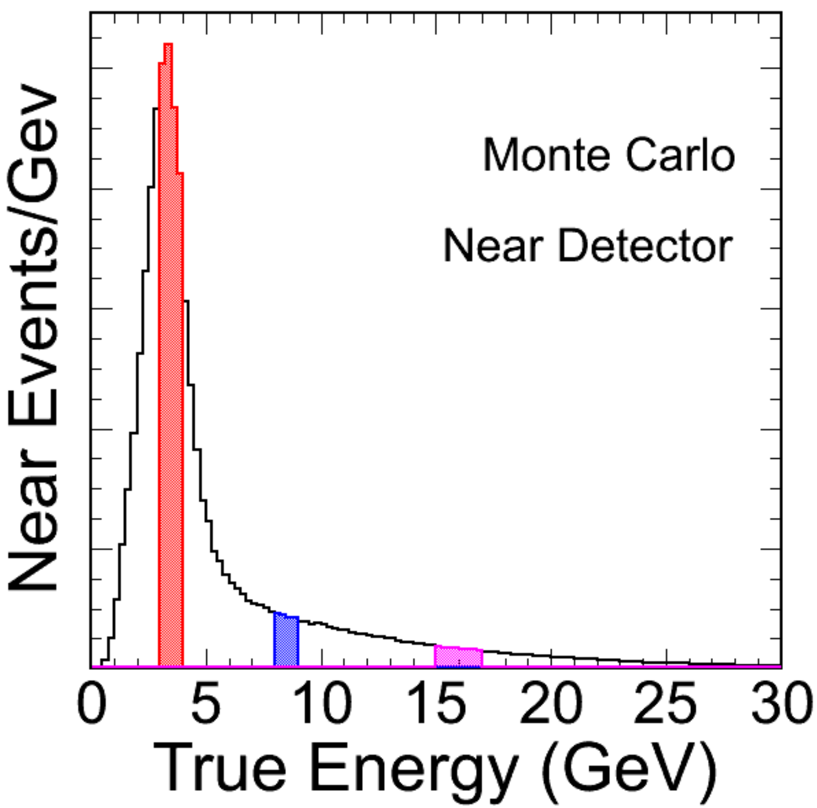
Systematic Errors – $\bar{\nu}_\mu$ RHC

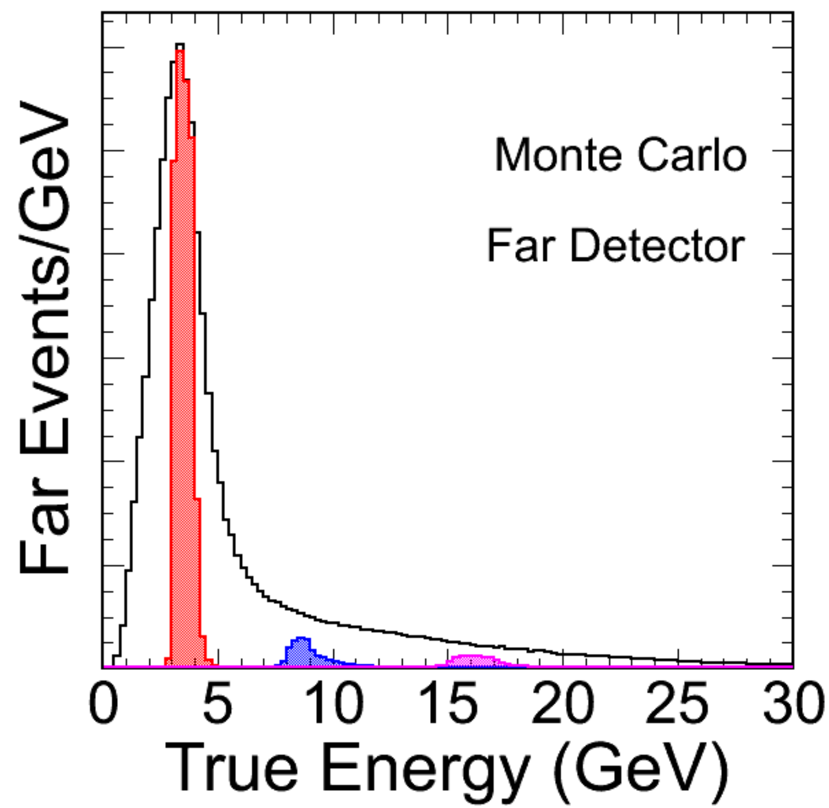


Beam Matrix: RHC $\bar{\nu}_\mu$



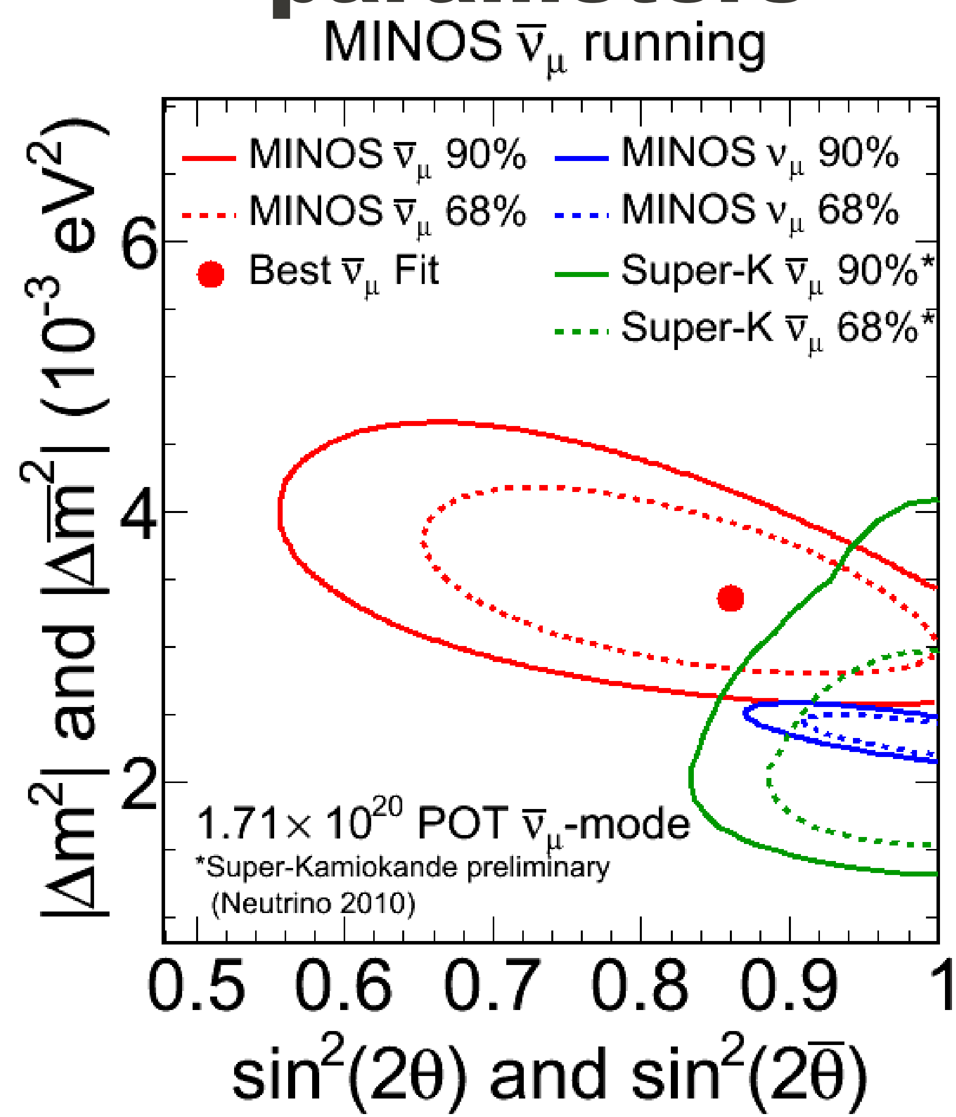
Far to Near Histograms



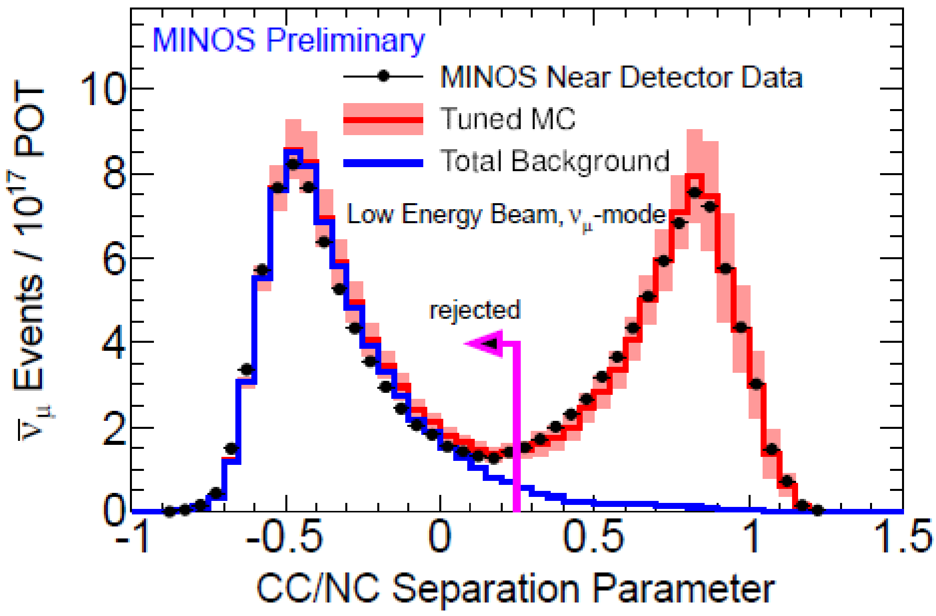


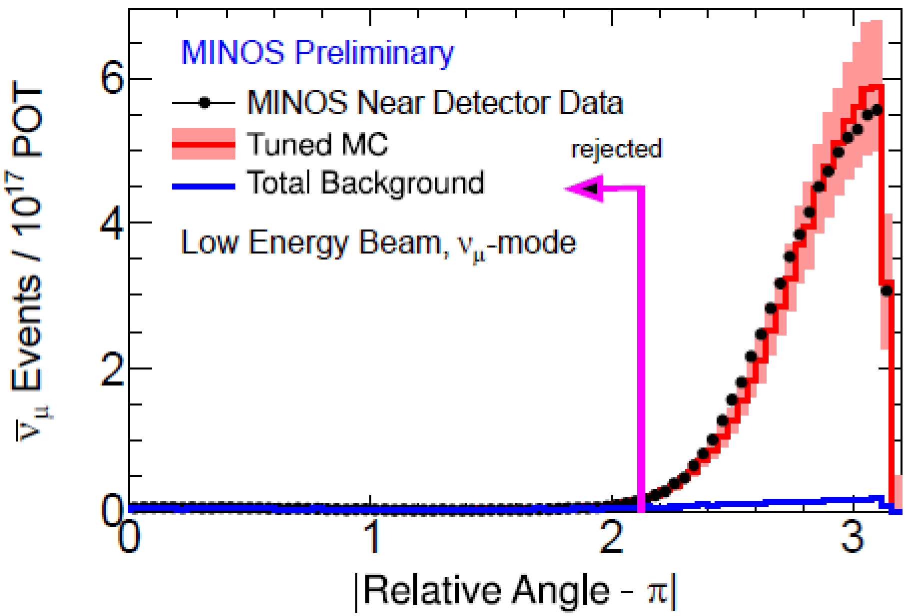
Agreement of ν_μ and $\bar{\nu}_\mu$ parameters

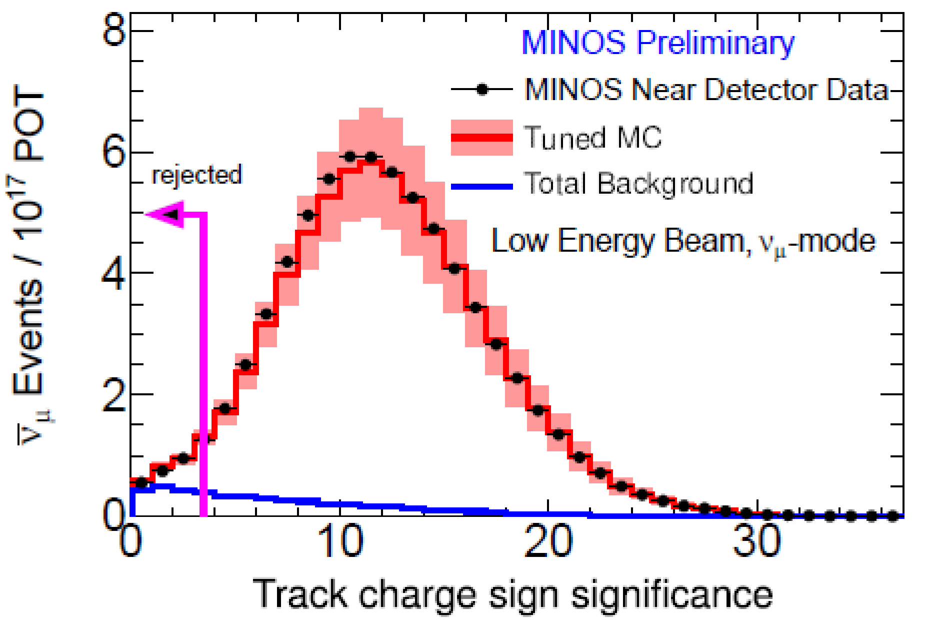
- Best fit ν_μ and $\bar{\nu}_\mu$ oscillation parameters differ modestly
- A 2 parameter joint fit to ν_μ and anti-ν_μ yields
  $|\Delta m^2| = 2.42\ eV^2$
  $\sin^2 2\theta = 0.96$
  with acceptable chi-square, but not as good as the 4 parameter fit.
- You can then ask, for the above parameters, how often do you expect a 4 parameter fit at least that much better than the 2 parameter fit?
- The answer is 2.0%



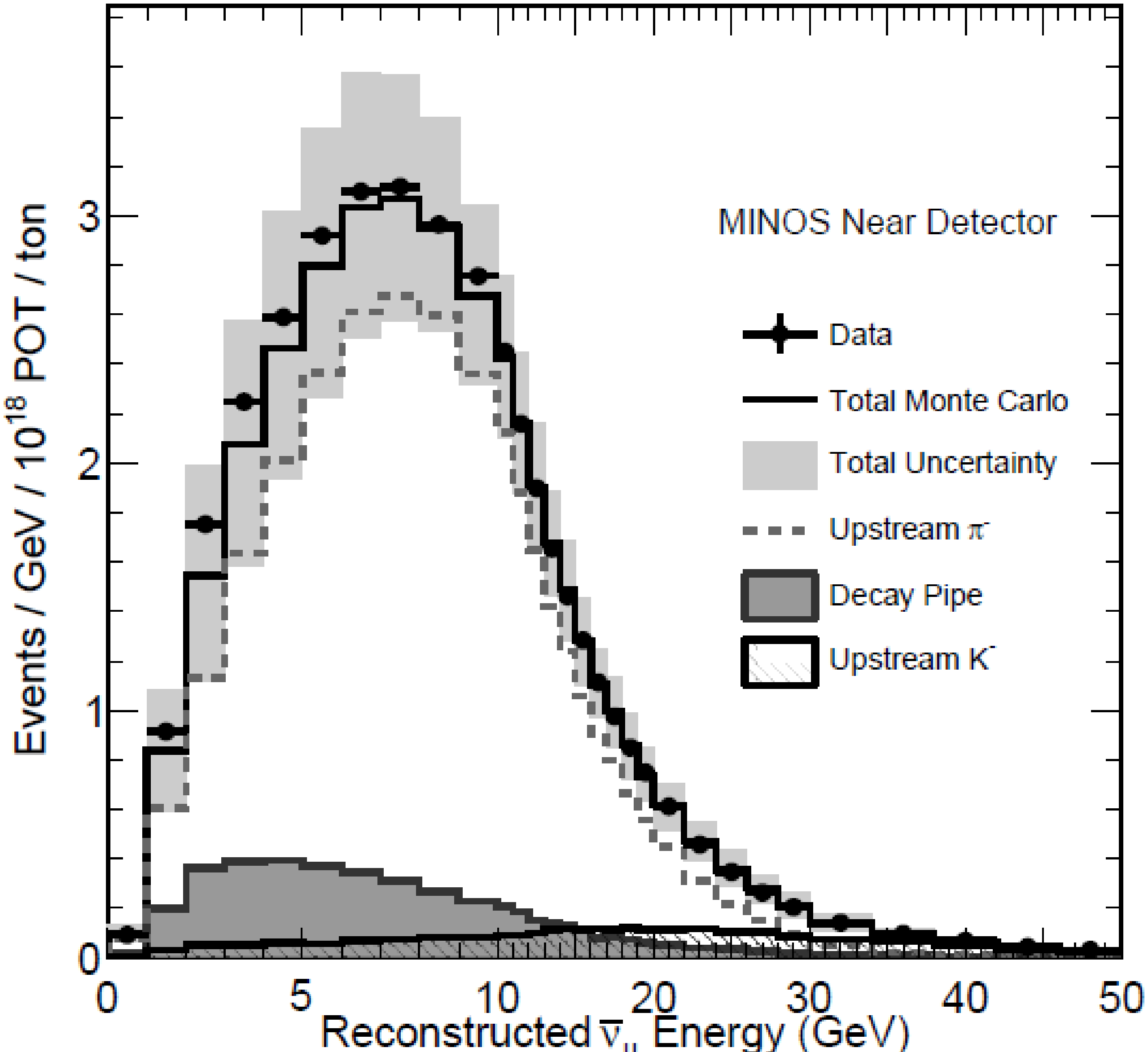
ν_μ-FHC Selection





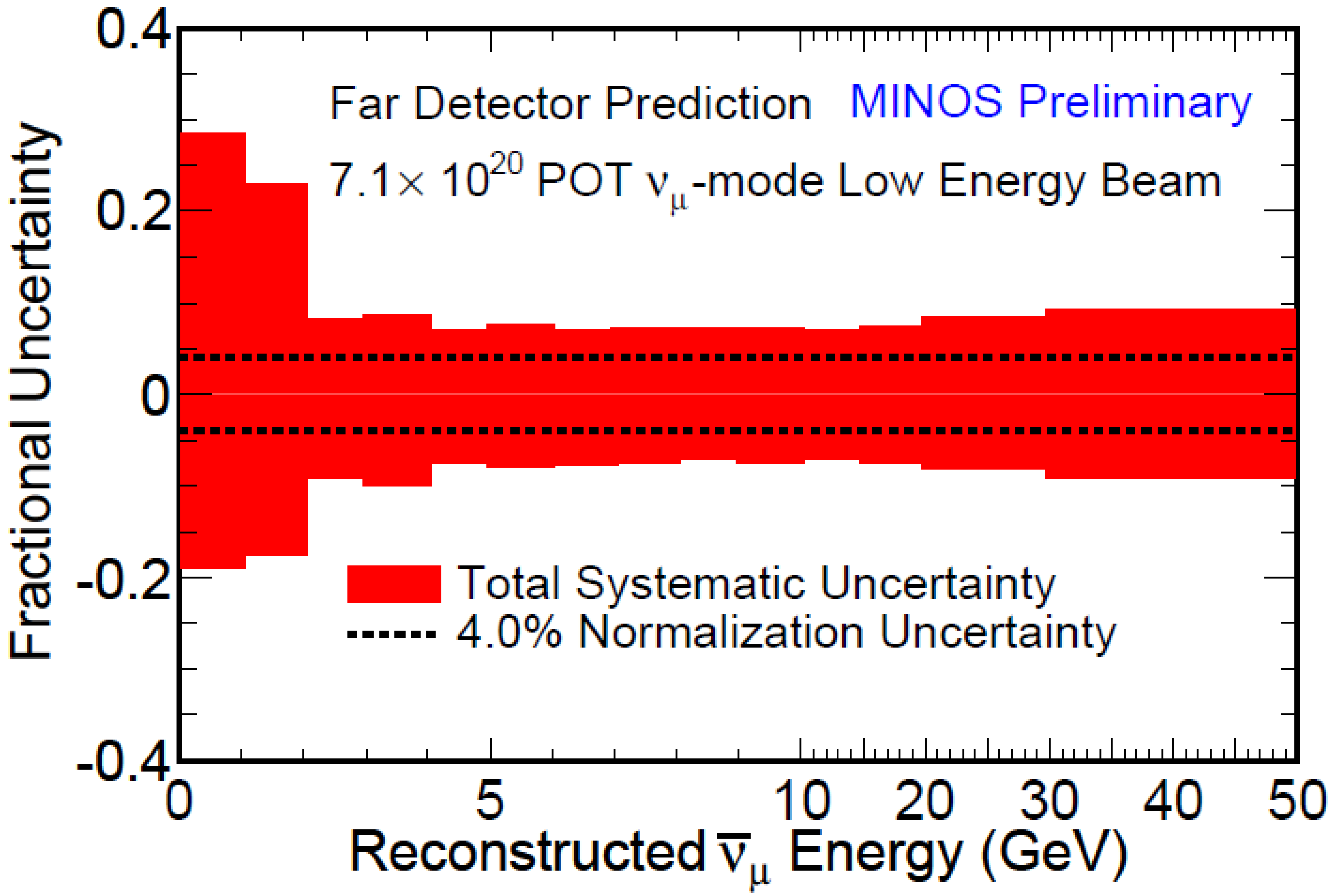


Systematics: $\bar{\nu}_\mu$-FHC



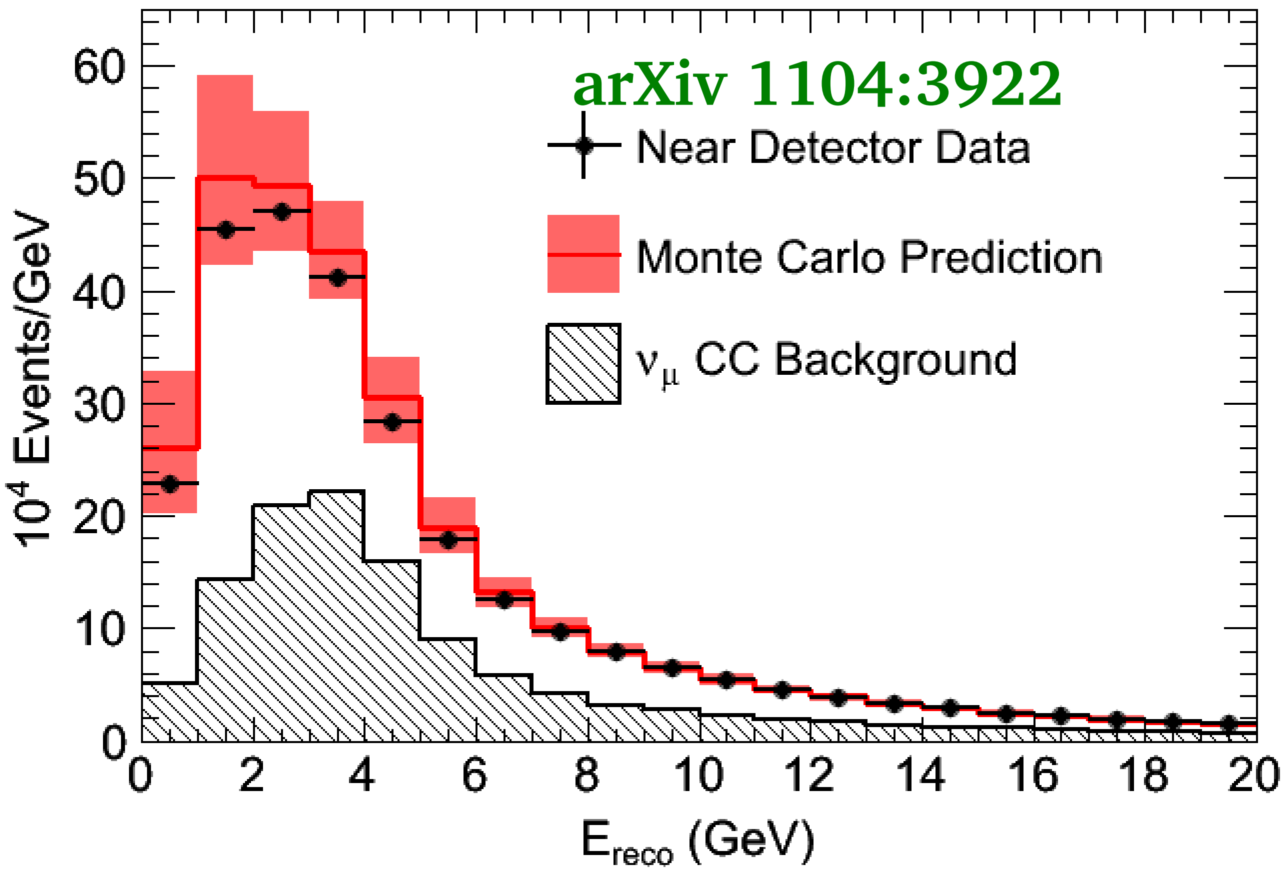
- Decay pipe 14% of ND, 6% of FD ν_μ-CC
  - uncertainty from scaling ND MC to data: +6.1%,-3.8% in FD
- 4% relative normalization
- 4% muon energy scale
- 50% on background from NC and ν_μ-CC

Systematics: $\bar{\nu}_\mu$-FHC

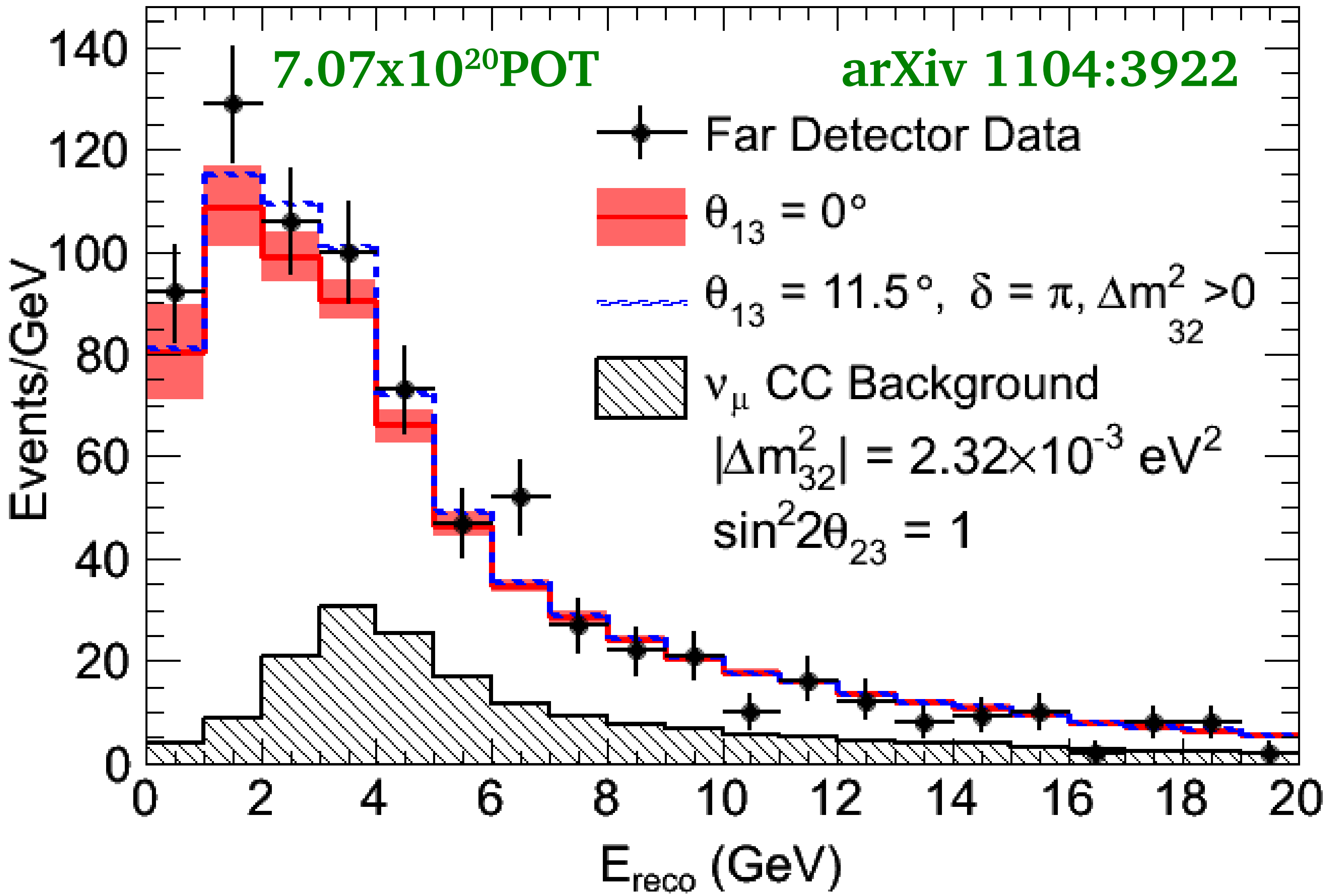


MINOS Sterile Neutrinos

- NC interactions measure the combined ν_e, ν_μ, ν_τ rate and are sensitive to mixing with a hypothetical sterile neutrino
- sterile neutrinos, or some other non-SM process needed to explain MiniBooNE/LSND



MINOS Sterile Neutrinos



MINOS Sterile Neutrinos

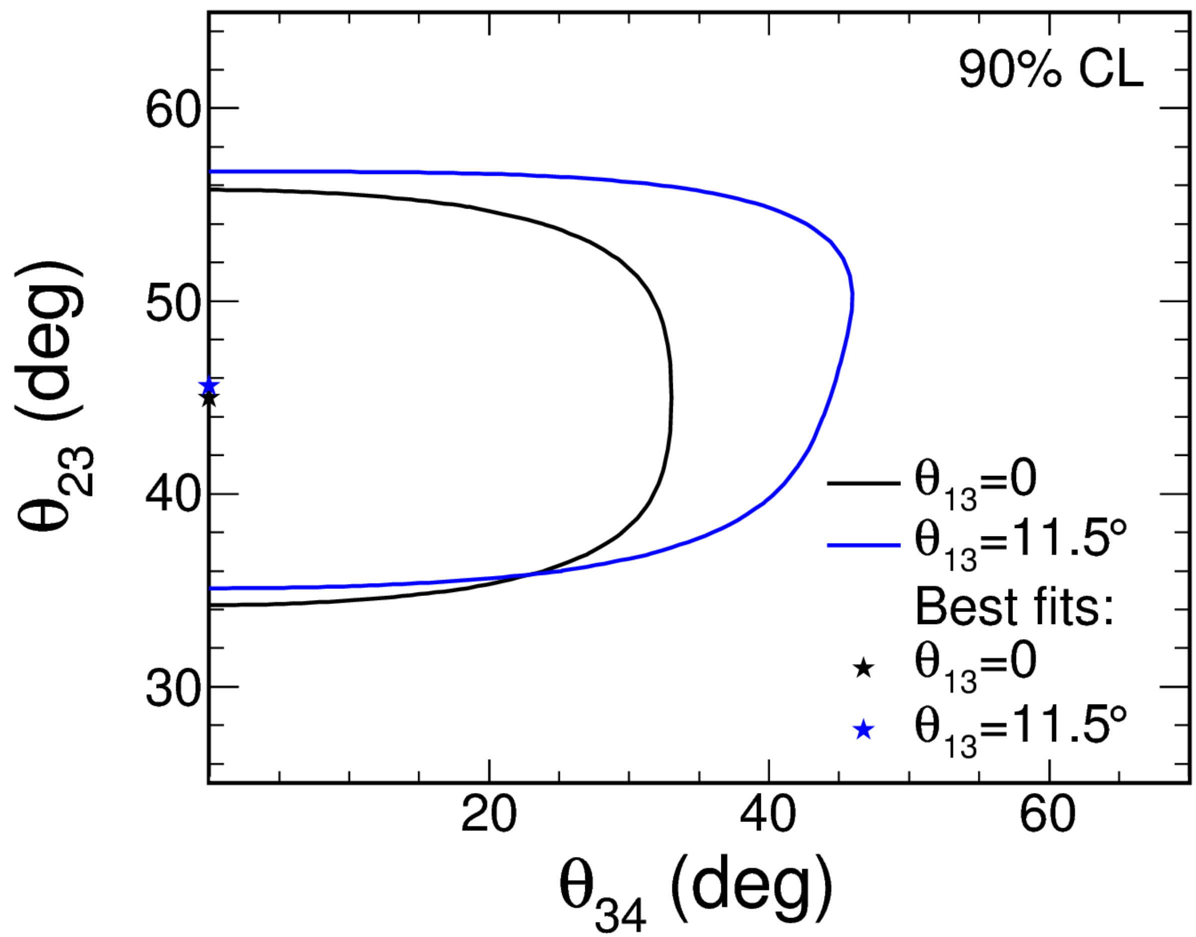
m4~m1 model

$\nu_\mu \rightarrow \nu_s$ oscillations occur with atmospheric L/E

Result

f_s <0.22 (0.40) @ 90% CL

$\theta_{13}=0^o$ ($\theta_{13}=11.5^o$)



MINOS Sterile Neutrinos

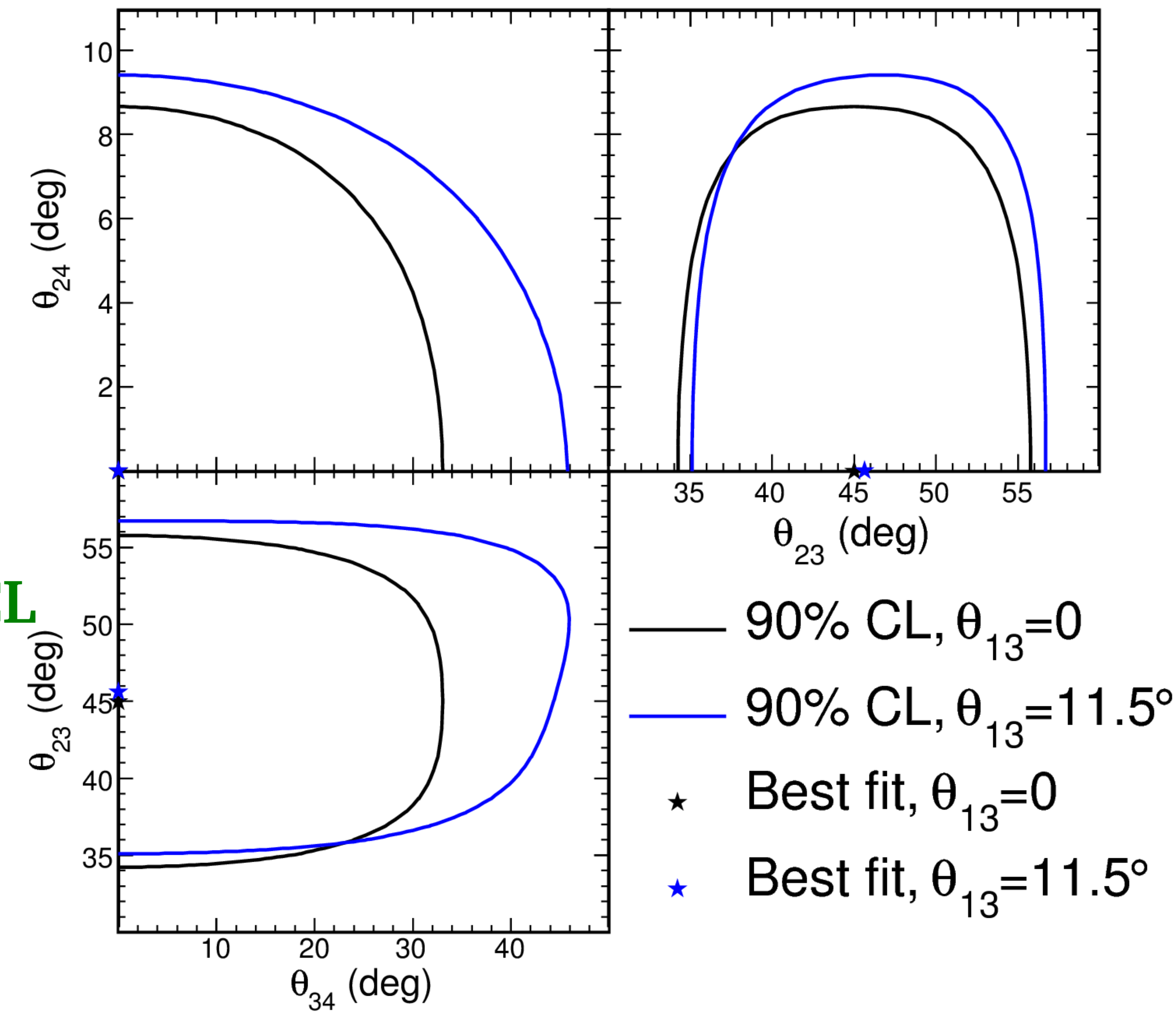
m4>>m3 model

$\nu_\mu \rightarrow \nu_s$ oscillations
with high mass scale
$|\Delta m^2_{43}| \sim 1$ eV^2

Result

f_s <0.22 (0.40) @ 90% CL

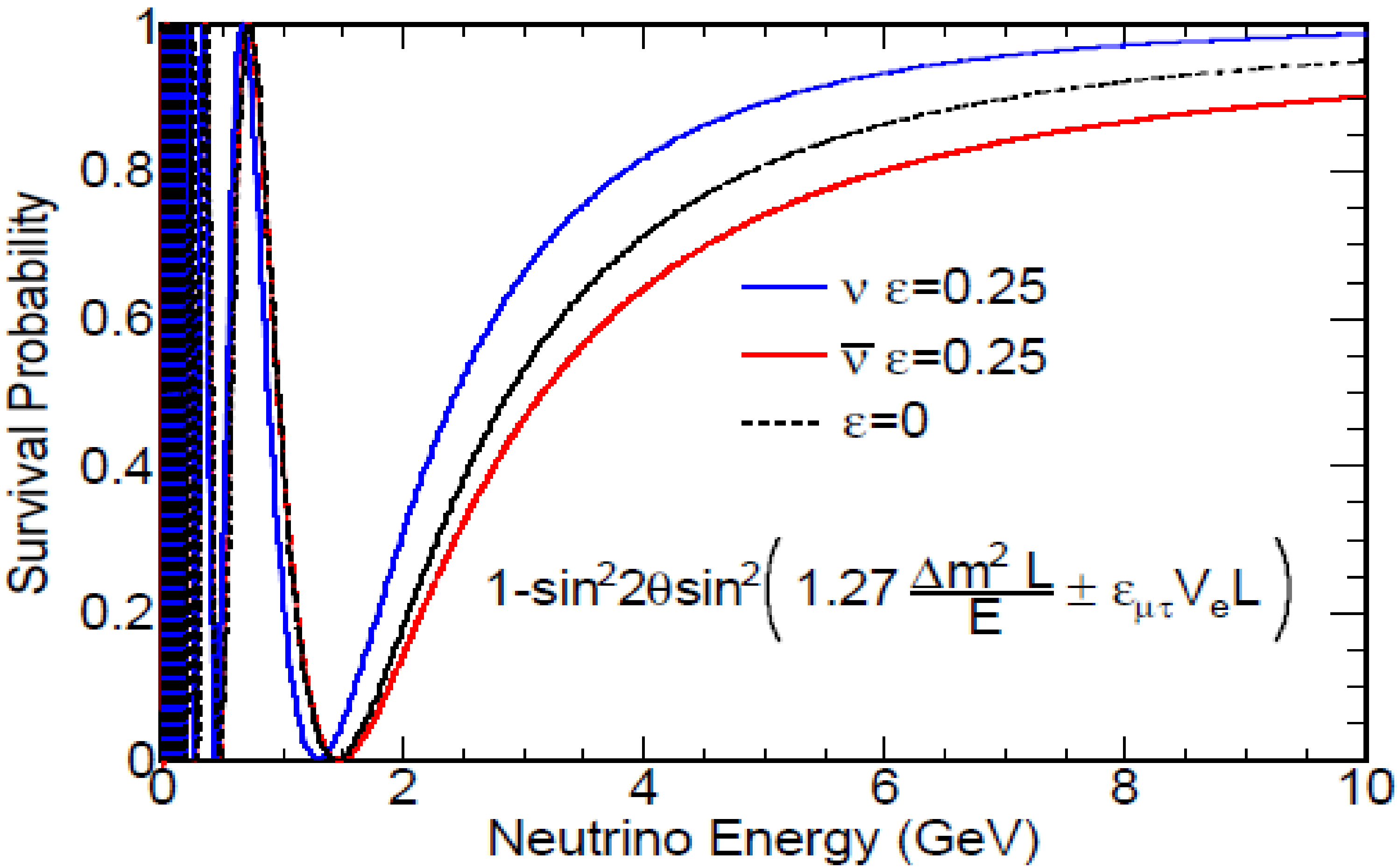
$\theta_{13}=0^o$ ($\theta_{13}=11.5^o$)



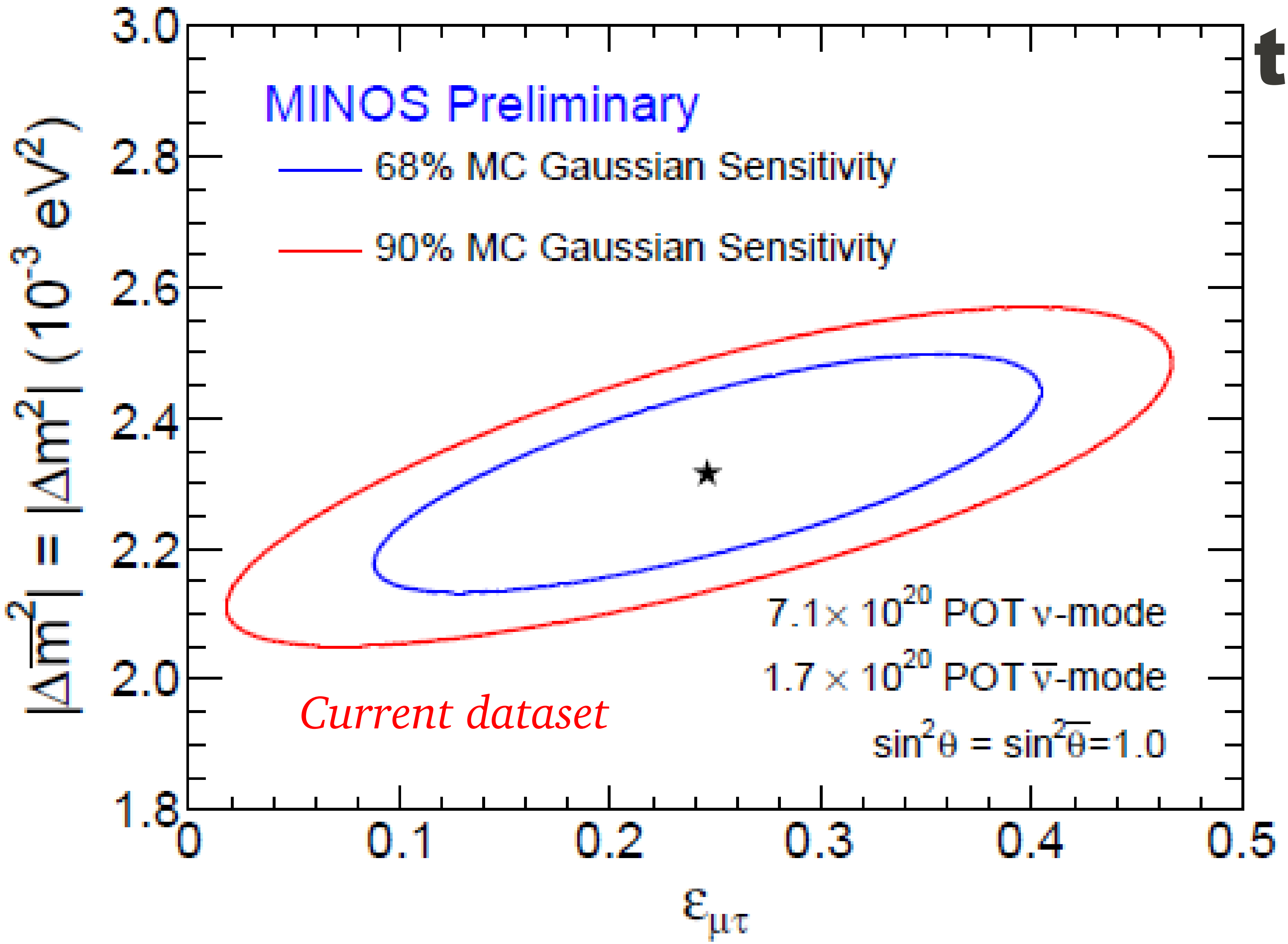
Non-Standard Interactions

CPT symmetry requires $P(\nu_\mu \rightarrow \nu_\mu) = P(\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu)$ in vacuum

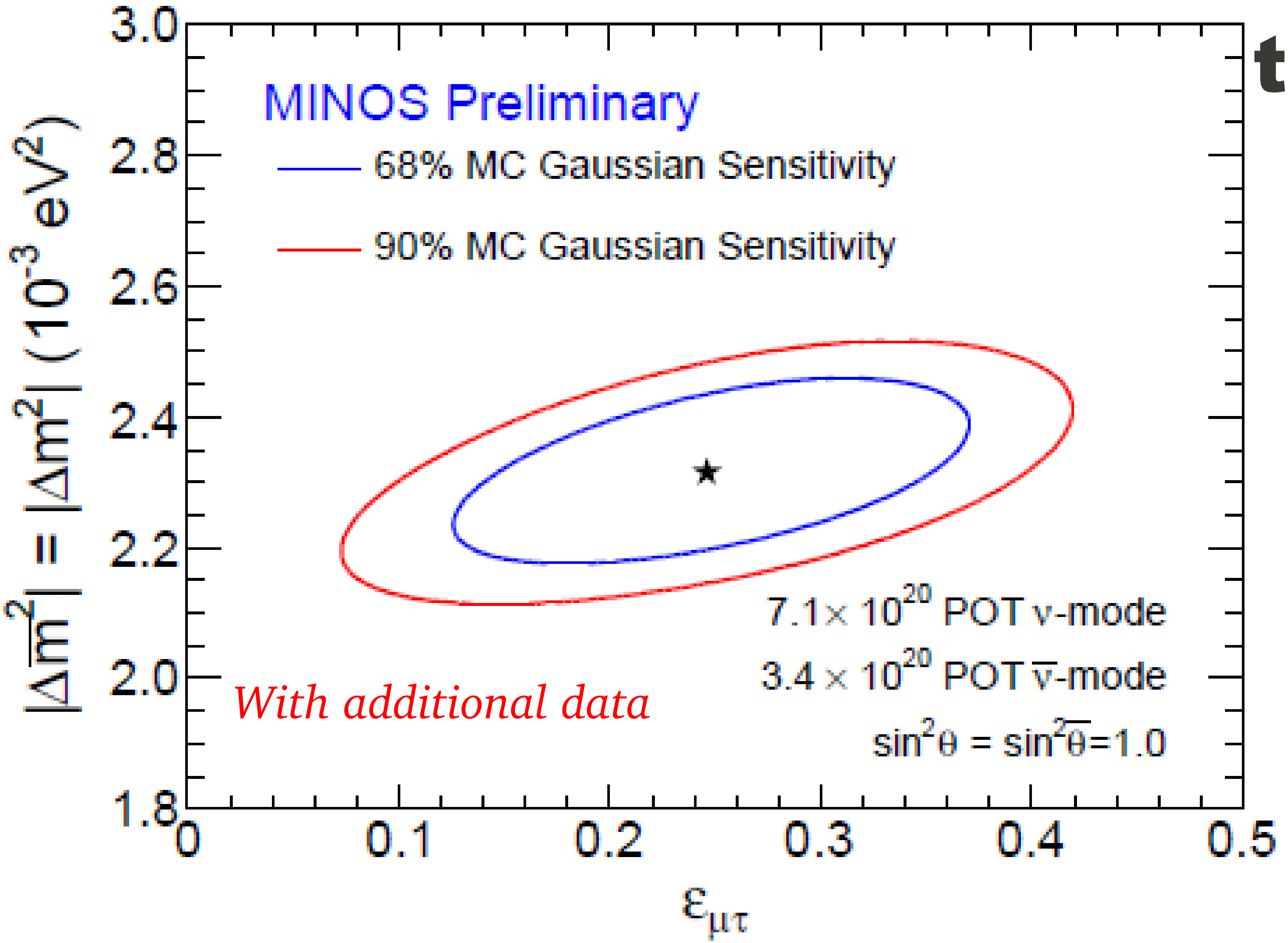
Non-standard interactions (e.g., due to some new force) modify the ν_e, ν_μ, ν_τ Hamiltonian and create matter effects analogous to MSW effect seen in electron neutrinos



MINOS Sensitivity to NSI



MINOS Sensitivity to NSI

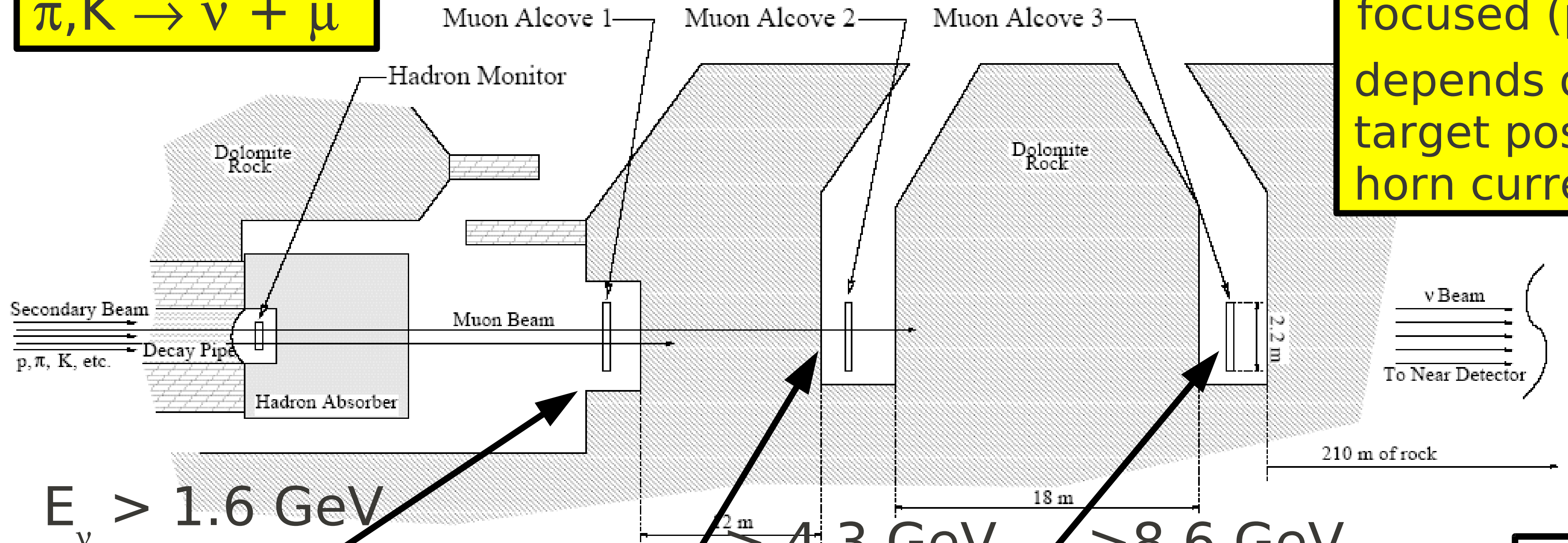


Monitoring

ν,μ spectra depends on (p_z,p_T) of π,K

π,K $\rightarrow \nu + \mu$

focused (p_z,p_T) depends on target pos & horn current



E_ν > 1.6 GeV

> 4.3 GeV

>8.6 GeV